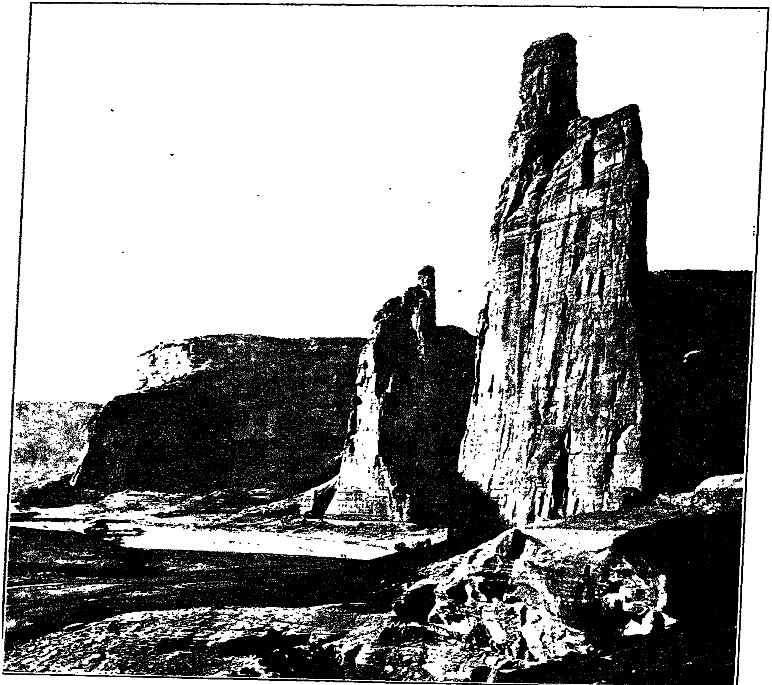

Captains of the Cañon, Rio de Chelly, Arizona.
(U.S.G.S.)

AN INTRODUCTION TO GEOLOGY

THIRD EDITION REWRITTEN THROUGHOUT

BY

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VOL. I

PHYSICAL GEOLOGY

With numerous illustrations from new photographs.

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"There rolls the deep where grew the tree.
O earth what changes hast thou seen!
There where the long street roars, hath been
The stillness of the central sea.

"The hills are shadows, and they flow
From form to form and nothing stands;
They melt like mists, the solid lands,
Like clouds they shape themselves and go."

TENNYSON

PREFACE

In spite of the interruption caused by the World War, the last twenty-five years have produced an immense quantity of geological literature and in endeavoring to incorporate the requisite amount of the new material in this book, it has been found necessary to rewrite it altogether and to adopt a new order of treatment. This order has been worked out in the laboratory and tutorial exercises of the elementary course and practically tested for half a dozen years by my colleagues, Professors A. F. Buddington and R. M. Field; the *Laboratory Manual* of the latter is followed in arranging the order of topics. At the same time, it is perfectly feasible to make use of the book in such different order of chapters as the instructor may prefer.

To enumerate here even the more important of the manifold additions made to the geological sciences in the last quarter of a century would be to write a summary of the book. A few of the more significant additions to the science should, however, be mentioned here.

There is, in the first place, a great addition to the knowledge of the igneous rocks, and their related topic, vulcanism. The work done by the Geophysical Laboratory in Washington and the various volcanic observatories, notably the United States Observatory on the Island of Hawaii, has quite revolutionized the older conceptions.

Of a very different type, but perhaps even more important, is the work accomplished by the numerous exploring and collecting expeditions sent out by the various museums; notably the work of the American Museum of Natural History in South America, in the Island of Samos, in India, and above all in the Gobi Desert of Mongolia. So significant are the discoveries made by these expeditions that it has seemed advisable to extend largely the sections on the geology of the continents other than North America, because they form a long step toward the much desired general history of the earth.

From the palæontological standpoint, also, the collections made in this manner have added immensely to our knowledge and to our comprehension of facts previously known. The questions of the origin and migrations of the various mammalian groups have thus received answers which but a short time ago would have seemed quite out of reach.

The palæontology of plants has been revolutionized by the discovery of many intermediate forms in China, in the Grand Cañon of Arizona, in Polish Silesia, and in other regions, which enables us to sketch an outline of plant evolution which is of the utmost interest.

A new feature of this edition is the section on Ancient Man, which was omitted from the earlier editions, and in them the theory of Evolution was not made use of, although the author was fully convinced of the truth of that theory. This attitude of reserve is abandoned in the present edition and Evolution is taken for granted as the only possible explanation of geological history, for the theory is accepted with almost complete unanimity by the scientific world.

The compiler of a text-book is confronted with a great difficulty in dealing with the many hypotheses and bold speculations which have, of late years, claimed the attention of geologists. Certain sane and sober men of science, who keep their feet on the ground, have made public protest against this pyramiding of unverifiable hypotheses. In fact, the outlook is at present ominous of a return to the days when Neptunists and Plutonists quarreled so fiercely and Catastrophism was the ruling belief. Professor Daly, who is not at all averse to speculation, thus concludes his chapter on the origin of mountain ranges, in *Our Mobile Earth*. "Throughout this whole discussion the reader will remember that speculation is not science or knowledge. Speculation, even of the happiest kind, can do no more than point the way to possible future knowledge. Though it may stand on the right path, the signpost is not the goal itself." These are words of wisdom which it were well to remember, but, while it is plain that an elementary text-book is no place for polemics as to speculative hypotheses, the beginner should be told something of the more significant trends of geological opinion, even though the author should be entirely skeptical of their lasting value.

When the second edition of this book was in preparation, I

learned, somewhat to my surprise, that text-books were quite largely used as works of reference, and, at the request of some such readers, who desired "to know the authority on which the more novel or less familiar statements had been made," many brief quotations, with their authors' names, were introduced. In this third edition, similar requests have led to the placing of references to titles at the end of each chapter. These lists are, in no sense, bibliographies or recommendations for students' reading; they are merely means of verifying or extending the statements made on the authority of competent investigators.

The work of revision has been much facilitated by the publication of certain excellent comprehensive works, with most useful bibliographies. Beside the new editions of Pirsson and Schuchert's *Text Book of Geology*, and Chamberlin and Salisbury's *College Geology*, there are the third edition of Professor Waldemar Lindgren's *Mineral Deposits*, the *Grundzüge der Geologie* by many collaborators, with Professor W. Salomon, of Heidelberg, as editor, and the *Grundzüge der Physischen Erdkunde*, by Professor A. Supan. The last-named book is considerably older than the others, but remains a veritable mine of information. Most text-books of Geology, including the two former editions of this one, treat fossil plants in somewhat "stepmotherly" fashion. Professor A. C. Seward's admirable new *Plant Life through the Ages* removes all excuse for this.

Acknowledgments

Whatever degree of success I may have attained in the work of rewriting is very largely due to unstinted and unwearied assistance on the part of my colleagues of the Department of Geology in Princeton University, who have most generously opened to me their stores of special knowledge. I am under particular obligations to Professors C. H. Smyth, Jr., W. J. Sinclair, and A. F. Buddington, who have read much of the manuscript. Their help has gone on through several years and in a great variety of ways, but in scarcely less degree I am indebted to Professors A. H. Phillips, Edward Sampson, W. T. Thom, R. M. Field, Paul McClintock, B. F. Howell, M. S. Farr, and Drs. J. R. Sandidge and Erling Dorf. I am likewise obliged to many kind friends, in different parts of the world, who have assisted me in various

ways. Professor W. Lindgren was so kind as to read the chapter on ore-deposits and suggest several emendations, which were gratefully adopted, and Professor Douglas Johnson and his secretary, Miss Rom, sent me advance sheets and diagrams from his forthcoming book, *Stream Sculpture of the Atlantic Rivers.* Professor C. P. Berkey has allowed me to use his cross-section of the Hudson River, sending me the original drawing.

In the course of years a very large collection of photographs has been gathered and for these I am almost entirely indebted to the good offices of friends, above all to the official surveys and museum staffs. Sir John Flett, director, and Dr. Howe, assistant director, of the Geological Survey of Great Britain, Dr. W. H. Collins, director of the Geological Survey of Canada, Dr. G. Otis Smith, former director and Mr. N. H. Darton, geologist, of the U. S. Geological Survey, have supplied me with so many and such choice illustrations that selection of the comparatively few that can be used has been most difficult. Drs. Charles Resser and J. B. Reeside, Jr., W. P. Woodring and Marshfield of the U. S. National Museum, most kindly undertook to select the specimens and oversee the drawings of the additional plates of fossils which Mr. Horsfall has made for this edition, and Dr. G. H. Girty has supplied me with valuable information by letter. Dr. Rudolf Ruedemann, palæontologist, and Miss Winifred Goldring, associate palæontologist, of the New York State Survey, have supplied many beautiful pictures of the treasures housed in the Albany Museum, while Dr. G. H. Ashley, State Geologist of Pennsylvania, has been equally kind.

Major General Squier and the officers of the Army Aviation Corps, I have to thank for the fine pictures from the air, which are reproduced in the text. The Aircraft Operating Company of London and Bulawayo have most courteously permitted me to reproduce their remarkable views of the Victoria Falls. Dr. T. A. Jaggar, director of the U. S. Volcanic Observatory, Hawaii, kindly sent me an uncommonly fine series of views of the Hawaiian volcanoes; it is much to be regretted that I have not space to reproduce them all.

The reader cannot fail to note the many illustrations taken from the unrivaled collections of the American Museum of Natural History, New York. These I owe to the kindness of my friend of nearly sixty years standing, Professor H. F. Osborn,

President, and to that of Mr. Walter Granger of the department of Vertebrate Palæontology and his assistants, Miss Husband and Miss La Monte. Dr. C. A. Reeds of the department of Geology has also given me material assistance, as has Mr. O. A. Peterson, of the Carnegie Museum in Pittsburgh, who has sent me the unpublished results of his work on the Tertiary of northeastern Utah. Professors W. H. Hobbs, of the University of Michigan, Bailey Willis, of Leland Stanford, and Mr. Harold S. Colton, of Flagstaff, Arizona, have supplied many fine prints, and friends abroad have been no less kind. To the New York office of the Swiss Federal Railways, I am indebted for the fine views of Monte Rosa and the Gorner Glacier.

Professor S. H. Reynolds, of the University of Bristol, has sent me such an instructive series of geological views, that I heartily wish I might use them all, and Dr. C. M. Yonge, of the Marine Biological Laboratory in Plymouth, has supplied the beautiful photographs of the Great Barrier Reef of Australia. Dr. F. Berckhemer, of the Naturalien Cabinet, in Stuttgart, had photographs especially made of some of the world-famed reptiles of the Stuttgart Museum. Dr. R. W. Sayles has sent me very full material, printed and photographic, of the Squantum Tillite. Professor R. B. Young, of Johannesburg, who supplied the figures of South African Palæozoic glaciation in the second edition, has again put me in his debt by furnishing new and additional ones. I must further mention the kind assistance given by Dr. E. C. Andrews, of Sydney, and the Great Barrier Reef Committee, of Brisbane, while Mr. James Greenlees, of Glenelg, South Australia, supplied an unusually interesting series of views from Australia and New Zealand. Mr. Charles R. Knight has, with great liberality, permitted me to use some of his copyrighted restorations and Mr. L. R. Schureman, of the Princeton School of Engineering, has made a large number of drawings, including all the maps. Finally, I must express to Mr. R. Bruce Horsfall my cordial thanks for the pains and skill which he has devoted to the new plates. It would be superfluous to praise Mr. Horsfall's work; that speaks for itself. What should be made known is the generous and self-sacrificing spirit in which he did this work and offered to do more, should it prove necessary. Limitations of space forbid me to mention all those who have met my requests for help in one or another particular with uniform courtesy, but I must find room to thank Mrs. Lena

Stevens and Miss Alice McDonough for their indefatigable care and patience in typing a more or less chaotic manuscript. Volume II had the advantage of the skill and experience in proof-reading of my daughter, Mrs. H. S. Agar, who took the utmost care to eliminate all typographical errors.

To this company of friends, acquaintances, and unknown correspondents, I take pleasure in expressing my most sincere and hearty thanks for the coöperation without which my task would have been well-nigh impossible.

W. B. S.

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AN INTRODUCTION TO GEOLOGY

CHAPTER I

PRESENT STATE OF THE EARTH

Geology is the history of the earth, its animals and plants, as recorded in the rocks.

The earth is a member of the solar system, which consists of the sun, the central mass, the planets which revolve around it, and their satellites. The planets lie in nearly the same plane and revolve in the same direction; they all rotate upon their axes as well as revolve around the sun. The four inner planets, Mercury, Venus, the Earth, and Mars, are relatively small and very dense, Mercury the smallest, then Mars next in size, and, between them, Venus and the Earth, which are of nearly the same diameter. The four outer planets, Jupiter, Saturn, Uranus, and Neptune, are far larger and of such low specific gravity that many astronomers believe them to be gaseous. The density of Saturn, for instance, is less than that of water. Between the inner and the outer groups of the *major planets* is the aggregation of *minor planets*, or asteroids, which range in size from 15 to 400 miles in diameter and of which some 600 are known. No doubt there is an almost infinite number of these bodies below the limits of visibility. Of the newly discovered trans-Neptunian Pluto, with its remarkable, comet-like orbit, it is still too early to speak.

Except Mercury and Venus, all the major planets have satellites. The Earth has one, which is larger relatively to the planet than any other moon; Mars has two, Jupiter eight, Saturn nine, Uranus four, and Neptune two. In addition to its nine moons, Saturn has two wonderful, concentric rings, which are quite unique in the solar system and make the planet the most remarkable of telescopic objects. The orbits of the planets are more or less elliptical, though not far from circular in form. In the case of the Earth, the axis is inclined $23\frac{1}{2}°$ to the plane of the orbit, and to this

inclination is due the change of seasons. The pole is not stationary, but describes a small circle some 30 feet in diameter; except for this phenomenon of nutation, most astronomers believe that the position of the axis and poles has never undergone any important change.

The sun, at the center, is a vast body of intensely heated gas and, though its specific gravity is very low, it contains more than 95 per cent of the mass of the entire solar system. As we shall see later, not only is all life upon the earth dependent upon the light and heat of the sun, but most of the energy which brings about geological changes in the earth is also derived from the sun.

In form the earth is nearly spherical, but is so flattened at the poles that the equatorial diameter is some twenty-six miles greater than the polar, a very small difference relatively, about 1/300th part of the long diameter. The earth has also much irregularity of surface, — the ocean basins and continental platforms, the mountain ranges, plateaus, plains, etc., etc., in short, the topographical features. In proportion to the size of the earth, however, these surface features are insignificant and the earth is relatively smoother than an orange.

Internal Constitution. Much has been learned from the study of earthquake-waves concerning the internal constitution of the earth and these waves show that the earth, at least the outer half of its diameter, is solid and of a rigidity equal to that of steel, while its elasticity is almost perfect. Nevertheless, the attraction of the sun and, more especially, of the moon produces tides in the solid earth as it does in the sea, though very much less in amount, which is a matter of six to eight inches twice every day. The specific gravity, or density, of the earth is 5.52, that is to say, it weighs more than five and a half times as much as a globe of water of the same size. The average density of the rocks which are accessible at and near the surface is considerably less than 3, and, therefore, the earth must be largely composed of materials which are much more dense than those which occur at the surface. To some extent, this higher density is due to pressure, but it is now generally believed that the globe must have a core of iron, no doubt containing nickel, like the metallic meteorites.

Internal Temperature. Near the surface, the temperature of the earth is due to the sun's heat, down to a depth which is determined by latitude and, at that of New York, is about 50 feet

below the surface. Below this level, where the temperature remains constant throughout the year, it steadily increases with depth, at a rate which varies greatly at different places, but the increase, whatever the rate, is found everywhere. The average rate of temperature increase, as determined in mines and borings for water, oil, and gas, is usually given as 1° F. for every 50 or 60 feet of descent, but it may be as rapid as 1° for 30 feet or as slow as 1° for 200 feet, but these artificial openings are far too shallow to enable us to estimate what the temperature of the deep interior may be. A temperature increment of 1° F. per 60 feet of descent is 88° per mile and, at such a rate, very great heat would be found at moderate depths. Volcanoes, which are so widely distributed over the earth's surface, show that, at least, in a great many places, the earth has an internal temperature of 1,800° F. (1,000° C.) not far below the surface. We may confidently infer that, below 25 or 30 miles from the surface, the whole interior of the earth is at a very high temperature.

The lines of equal temperature, or *isogeotherms*, follow the irregularities of the surface, though with diminished steepness of slope, and they rise into the continental mass from beneath the sea bed. Off the west coast of Africa, at a depth of 2,000 fathoms, the temperature of the water is 33° F., while at a corresponding depth beneath the African plateau, which is 5,000 feet, or more, above sea-level, the temperature would be 356°, allowing an increment of 1° for every 50 feet of descent. At the depth of a few miles, however, all effect of surface irregularities must disappear; but, beyond saying that the interior of the earth is very hot, it is impossible to determine what its temperature actually is.

Arrangement of the Earth's Component Parts. The outermost part of the earth, the *atmosphere*, is gaseous; the incomplete covering of water is the *hydrosphere;* the outer solid portion the *lithosphere.* As before stated, astronomical observations and earthquake waves indicate that the earth, except, perhaps, its central core, is as rigid as a globe of steel, but that refers to stresses of short duration. Long-continued stresses produce a slow, plastic yielding to deformation, as do many substances such as pitch, sealing-wax, etc. These are all brittle under sudden blows, but yield to deformation under slow pressure. The same data indicate that the material of the earth is arranged in concentric shells, each shell so different from those next to it, outside and in,

that earthquake waves change their velocity and are refracted or reflected on passing from one to the other, just as are light waves which pass from air to water or water to air. While there is very general agreement among geologists as to this arrangement of concentric shells, there is much difference of opinion concerning the actual material of these shells. Comparing the cross-section of the earth published by various writers within the last thirty or forty years, one finds a fundamental agreement between them with considerable difference in matters of detail. All accept the central core of iron, containing nickel and relatively small amounts of platinum, gold, and other metals; in diameter this core is estimated to be somewhat more than one-half that of the earth and in volume about one-sixth. Surrounding the core is a shell about 1,400 miles thick, made up of silica compounds, the material of ordinary rocks, and this composes some three-fifths of the earth's volume. The outer shell is itself divided into three parts: there is the outer crust, 40 to 60 miles thick; a substratum of heavy and basic material, such as basalt or peridotite; and a transitional shell with iron disseminated through stony material and increasing proportionately downward, until it merges into the iron core.

Meteorites are believed to indicate the structure of a planet of which they are fragments and range in composition from the purely metallic, chiefly nickeliferous iron to the stony without metals, through intermediate stages in which the nodules of iron diminish to zero. The observations of Geiger and Gutenberg place the boundaries of the outer shells in round numbers, at depths of 720, 1,020, and 1,470 miles below the surface. At a depth of 30 or 40 miles there is a sudden change in the nature of the earth's material and this is taken as the thickness of the outer crust. Here, some earthquake waves are refracted on passing from the crust to the substratum, while others are totally reflected.

According to Professor Daly's views concerning the structure of the outer portion of the earth, each continent is a mass of granite, a kind of rock which is confined to the continents, resting upon a substratum of crystalline basalt, which, in turn, rests upon glassy basalt, hot enough to melt at surface pressures, but solidified by the pressure of the crust. Bowen, on the other hand, believes that the substratum must be some rock even more basic than basalt, such as peridotite or dunite. Certain German geologists (*e.g.*, Prof. Königsberger, of Freiburg) hold that there is a molten

layer beneath the crust, a conclusion which would seem to be inconsistent with the subcrustal structure revealed by earthquake waves.

Diastrophism means differential movements of parts of the earth's surface, upward, downward, or horizontal. Geological history shows that nearly all the continents have, at one time or another, been more or less completely submerged by the sea and this repeated submergence and emergence is, in most instances, due to elevation and depression of the land rather than to changes of sea-level. As will be more fully shown in Chapter IX, rising and sinking of the land are still in progress. Often these changes of level are sudden and abrupt and, in such cases, they are always associated with earthquakes, but frequently the rising and sinking are very gradual and imperceptible except after long intervals of time.

Diastrophism is of two kinds: (1) the *orogenic*, or mountain making, and (2) *epeirogenic*, or continent forming. In orogenic diastrophism, the originally horizontal beds of rocks are compressed and folded, or fractured and overthrust, and such compression affects long, relatively narrow belts of rocks, while epeirogenic movements are of direct uplift, or, much more frequently, of gentle warping, upward or downward, as the case may be. Such movements may affect areas of any size or shape, but are seldom narrow bands, such as mountain ranges typically are. It is to diastrophism that are due the irregularities of the earth's surface and the continued existence of the lands. Were it not for diastrophism, the lands would long ago have been worn away and covered by a universal, unbroken sea.

Isostasy. The great irregularities of the earth's surface, such as the continental masses, mountain ranges, and plateaus, are not supported by the rigidity of the crust, but float, as it were, upon the subcrustal rock material. This material, while rigid as steel to stresses of short duration, yields plastically to long-continued deformation. Under mountain ranges there is a deficiency of density, under the oceans an excess. Above the level of compensation, which is estimated to be about forty miles below the surface, segments of the crust of equal surface area have the same mass or weight, though they may differ by many thousands of feet in vertical measurement. One such segment may carry a lofty range of mountains, while the surface of an adjoining seg-

ment may be a low-lying plain. Such a condition of balance is called isostasy, and it follows that any segment which is loaded by the deposition of material upon it must sink under that load, while areas which are lightened by the removal of material must rise. Compensation is effected by the slow, lateral transfer of subcrustal material.

The Glacial Ages, which came very late in the earth's history and ended but a few thousand years ago, may be looked upon as a great series of experiments in isostasy. North America, down to latitude 40° N., and Europe to latitude 50° N., were covered with sheets of flowing ice, as are Greenland and Antarctica today. The continents sank under this enormous load, and when the load was removed by the melting of the ice, the land rose correspondingly. How slow this adjustment is, is shown by the fact that the glaciated areas in Europe and North America are still rising, though thousands of years have passed since the ice disappeared from those continents.

If the subcrustal material, the lateral transfer of which brings about isostatic adjustment, were of the same density as the earth's surface rocks, isostasy would preserve the irregularities of surface, for loaded areas would sink and unloaded ones rise by the amount of their loading and unloading respectively. As, however, the subcrustal material, the transfer of which compensates for the loss or gain of material at the surface, is much denser than the surface rocks, irregularities may be removed. We have evidence that ancient mountain ranges, such as the Appalachians, have more than once been worn down almost to sea-level.

The earth's interior is not homogeneous, when a given level is followed horizontally, for the Pacific hemisphere is denser than the Atlantic and other local irregularities have been observed. These differences are insufficient to produce any perturbation or "wobbling" in the rotation of the globe.

Continental Drift. Mr. F. B. Taylor in this country, and the late Dr. Alfred Wegener in Germany, have independently propounded a hypothesis that, down to a late geological date, the continents formed a single great land-mass and then slowly drifted apart until the existing arrangement was reached. So far, this hypothesis has not passed beyond the stage of an interesting speculation, but so many geologists, especially in Europe, are accepting it, that it cannot be ignored.

Land and Water. Because of incomplete knowledge of the polar regions, and especially of Antarctica, the area of the land and sea cannot be estimated with precision. But even when the polar regions shall have been accurately surveyed and mapped, the present estimates cannot be materially changed. According to these estimates, the land occupies approximately 29 per cent and the sea approximately 71 per cent of the earth's surface. In other words, the area of the sea is about two and one-half times that of the land, but the cubic quantity of water below sea-level exceeds that of land above sea-level in much greater proportion. The land-masses are distributed very irregularly in the universal sea and there is far more land in the northern than in the southern hemisphere. If the globe be so divided that all of the Pacific Ocean is included in one hemisphere, that hemisphere will have hardly any land. It is possible so to divide the globe into equal hemispheres that almost all the land will be in one and the greater part of the sea in the other. In such a globe, the north pole would be on the coast of France and the south pole near New Zealand. In the southern hemisphere, thus formed, the only land, other than small islands, would be Australia, New Zealand, Antarctica, and the southernmost tips of Africa and South America.

The principal bodies of land radiate in three lines from the north pole and it is possible to go from any point of the Arctic coast to Cape Horn, the Cape of Good Hope, or to the southern shore of Australia without losing sight of land. This arrangement of the land in three radiating masses has been of the utmost importance in facilitating the spread of terrestrial plants and animals over the earth. The distribution of land and water on the earth's surface, irregular as it seems to be, results in a sort of compensatory balance. The antipodes of almost every point on the land are in the sea, though, because of the vastly greater extent of the sea, the converse statement would not be true. The Arctic Sea lies in a deep depression around the north pole, while at the opposite end of the earth's axis is Antarctica, a lofty land-mass of approximately the same size as the Arctic Sea.

The Sea. The mode of dividing the universal sea into oceans is more or less arbitrary and differs much in different books. School geographies generally recognize five oceans, but most modern geographers accept only three, or even two: the Atlantic and the Pacific. The Arctic is really part of the Atlantic and

the Indian of the Pacific, while the Antarctic is the junction of the two great oceans. Whatever classification is used, the sea is one and indivisible and every part of it is in communication with every other part and the continents are islands in the universal sea.

It is entirely due to the irregularities of the earth's surface that there is any dry land at all; if the surface were actually smooth, the globe would be uniformly covered with water to a depth of about two miles. The depth of water varies much in different parts of the sea, and despite the many lines of soundings which have been made across the oceans, by far the greater portion of the sea is of unknown depths, but it is generally estimated that the average is 2,000 fathoms, or 12,000 feet. Each ocean occupies a profound depression of the earth's surface, from which the continents rise steeply.

Very frequently, the true ocean basin begins at the 100-fathom line, which is therefore generally taken as the boundary between deep and shallow water. With the old hand sounding-line it is generally impractical to sound in depths greater than 100 fathoms and such depths are said, in sailor parlance, to be "off soundings." As a general rule, the sea-bottom slopes very gradually from the shore to the 100-fathom line, at which the steep descent to the ocean-floor begins, but there are so many exceptions to this rule that some geographers attribute no significance to the 100-fathom mark. Off the west coast of Ireland, the steep descent of the bottom begins at the 200-fathom mark and at the mouth of the Congo, on the west coast of Africa, it is the 50-fathom line. The submerged border of the continent, known as the *continental shelf*, varies greatly in width.

Along the eastern coast of North America the continental shelf is 100 miles or more in width, but is not everywhere distinctly marked. Off the Carolina coast, for instance, the bottom slopes gradually from the low-tide mark to very deep water without any notable change of grade. On the other side of the Atlantic, the shelf is very wide in northern Europe, extending to two hundred miles west of Ireland and uniting Ireland and Great Britain to the continent. The Irish and the North and Baltic seas are on the shelf, which rapidly narrows to the southward and is only a few miles wide on the French and Spanish coasts of the Bay of Biscay. The average seaward slope from the western edge of the continental shelf is 13° or 14°, but is sometimes very much steeper.

Where the French cable from Brest to New York passes down the continental slope, the angle is 30° to 41°, grades as steep as those found in the Alps. On the Pacific side of both North and South America, the shelf is very narrow, only 10 to 15 miles in width. The area of the continental shelves throughout the world is estimated as rather more than 50,000,000 square miles.

The ocean-floor is remarkably flat, with very gentle grades, but there are elevations and depressions; the greatest depth of a depression is called a *deep* and those which give soundings of more than 3,000 fathoms have received names. The deeps are not, as a rule, in mid-ocean, but in narrow trenches near the foot of the continental slopes. The Atlantic Ocean, North and South, is divided into two depressions by the Central Rise, over which the water is 1,000 to 1,500 fathoms deep and which, beginning at Iceland, has been followed to 55° south latitude, a distance of 7,500 miles. At 51° north latitude the rise expands into a plateau, and there is another plateau upon which the Azores stand.

On each side of the rise is a trough, which widens into basins; the western trough expands northward into the North American Basin, the greatest known sounding in which is one of 4,561 fathoms in the Porto Rico trench. To the south the trough widens into the Brazilian Basin, great spaces of which are more than 2,500 fathoms deep and the greatest known depth of which is 4,030 fathoms in the Romanche Deep, which lies almost on the equator. On the eastern side of the Central Rise the trough is not so deep, though soundings of 3,300 fathoms have been made in the North African Basin and of 3,284 fathoms in the Peake Deep near the Azores. In the broad simplicity of its topography, the floor of the Atlantic Ocean is unlike any known land-surface and the same may be said of the other oceans also.

The foregoing is the account usually given of the topography of the deep-sea floor and is probably quite accurate for that part of the North Atlantic which has been repeatedly sounded for the submarine cables, but the cruise of the German naval surveying ship *Meteor*, which made 13 profiles across the ocean and over 33,000 soundings in the South Atlantic, has produced much unexpected information. Using the sonic method of sounding, which was developed by the United States Navy during the World War, the *Meteor* was able to take a sounding every 20 minutes while the ship was at sea. The reports of the cruise are not yet accessible,

but from preliminary accounts it is plain that very little has been known hitherto as to the conformation of the deep-sea floor, which, in the South Atlantic at least, is far more irregular and broken than had been supposed.

Inclosed, nearly land-locked seas, such as the Mediterranean, the Caribbean, the Gulf of Mexico, and the Arctic Sea, may be of truly oceanic depths, as all of those named are. The history of the Mediterranean, for example, is of great geological significance; this sea is demarcated from the Atlantic by a submarine ridge, on which the water is nowhere more than 175 fathoms deep, and which runs from northwest Morocco to southwest Spain. The sea itself is made up of three basins. The western or Balearic Basin, from Gibraltar to the rise on which Sardinia and Corsica stand, has a maximum depth of 1,742 fathoms; the Tyrrhenian Basin, between the Sardinian Rise and the coast of Italy, is nearly 2,000 fathoms deep; and the Eastern Basin, from Italy to Asia Minor, has large areas more than 2,000 fathoms deep. Italy, Sicily, and Tunis are connected by a rise which is covered by water nowhere as much as 200 fathoms deep, and mostly less than 100 fathoms. The Gulf of Mexico and the Caribbean Sea are simple, flat-floored basins, so far as they are known.

Fringing seas, such as Bering Sea, the North Sea, and the Baltic, are all relatively shallow, less than 100 fathoms in depth, and all have repeatedly been land-surfaces; their bottoms were land at a very late geological period. Hudson Bay is an example of an epicontinental, or epeiric sea — shallow water which has submerged large areas of land to an average depth of only 70 fathoms. The distinction between the shoal-water fringing and epicontinental seas on the one hand and the ocean basins on the other is of fundamental geological importance.

Permanence of Ocean Basins. There is much reason to believe that the great depressions, which form the oceans, and the continental platforms date from the remotest geological antiquity. This, however, is a debatable thesis and it is impossible to present the arguments, pro and con, in an elementary textbook; only a few of the reasons for this belief can be stated here. Before the deep sea had been explored, geologists assumed that sea and land had frequently changed places, so far at least as the much smaller area of the land would permit. The geological record, however, shows that, from the earliest recorded time, there has always been

land on the site of the existing continents. With, perhaps, the exception of Africa, all of the continents have been extensively submerged beneath the sea and their surfaces are, to a very large extent, made up of marine rocks. These repeated submergences were, in nearly all cases, beneath shallow epicontinental, or fringing seas, not oceanic depths.

The ocean basins have a topography so different from that of the land as to make it very improbable that any large areas of the sea-floor have ever been land; no sunken continent has been revealed by the sounding line. This does not imply that narrow isthmus-like land-connections may not have been carried down to great depths and some such connections are suggested by submarine rises and ridges which are not covered by truly oceanic depths of water. One such connection, which is made exceedingly probable by many independent lines of evidence, is that between South America and Antarctica by way of the Falkland and South Shetland islands. A bathymetrical map of the Antarctic Sea clearly indicates this line of connection. A similar connection is suggested by the rise which separates the Arctic and North Atlantic basins and supports the Faroe and Shetland islands, Iceland and Greenland. Conversely, the islands which fringe the Banda Sea show evidence of having been raised from great depths, but this is very exceptional.

A belief in the permanence of the ocean basins was long held by most geologists, but has been waning of late, and map-makers now raise continents out of the deep sea as they did before the time of Darwin and Dana.

The Taylor-Wegener hypothesis of continental drift is not essentially opposed to a belief in the permanence of the oceanic depression. Continental drift does not imply the elevation of sea-bottoms into land, or, conversely, the depression of land into the deep sea, but the slow movement, horizontally, of the continental masses over the sea-bottom.

The Land. Like the exact areas of land and sea, the average elevation can be given only approximately, because of uncertainty as to the altitude of great unexplored areas, such as the interior of Brazil and the Antarctic continent. Excluding Antarctica, the average elevation of the continents above sea-level is about 2,275 feet (700 meters). From the distribution of barometric pressures, Antarctica is estimated at the remarkable height

of 6,500 feet, and this, if confirmed, will raise the average for all the lands to 2,600 feet. About one per cent of the total surface of the earth (*i.e.*, including the sea) is more than 10,000 feet above sea-level, only 5½ per cent of the whole is higher than 3,250 feet (1,000 meters) and 10½ per cent is below 750 feet. Comparing these proportions with those of the sea-bottoms at various depths, we find that the submerged continental shelf makes up between 4 and 5 per cent of the earth's surface; 23 per cent is between 2,000 and 2,750 fathoms, and 2 per cent between 2,000 and 5,500 fathoms. These estimates show how much greater is the depression of the ocean-floor below sea-level than the elevation of the continents above it. In other words, the cubic content of the water is vastly in excess of that of land above sea-level — nearly 30 times as great.

The land-surface is much more diversified than is the bottom of the sea, plains, plateaus, hills, valleys, and mountains being the principal elements of topography. Plains are the more or less flat and low-lying parts of the land, though they may gradually rise to great heights, as do the Great Plains of western North America. At their eastern border these plains are but little above sea-level, but rise westward almost imperceptibly, until, at the foot of the Rocky Mountains, they have an altitude of 5,000 feet or more. The plateau, or table-land, is an elevated plain, but the distinction is not only in height, for some plains are higher than some plateaus. The western part of the Great Plains is more than twice as high as the Cumberland Plateau of Kentucky and Tennessee. The difference is that, at least on one side, the plain is abruptly bounded by higher, the plateau by lower land. From Long Island to Texas, the Atlantic and Gulf shores of the United States are formed by the low-lying, almost flat Coastal Plain. On the landward side this is demarcated by the Piedmont Plateau, which is of no great height, and if the sea came to its foot, as it formerly did, the plateau would be called a plain.

Between plateau and mountain the distinction is not always obvious, but one characteristic difference is in the summit area, which, in the plateau, is always considerable and may be very great, and, in the mountain, is small in proportion to its height. Plateaus may be greatly cut up by rivers and atmospheric agencies and are then said to be "dissected." Detached fragments of a plateau, which retain the original flatness of their

tops, are called table mountains, or, if low, have the Spanish name *mesa*.

Changes of Surface. The earth is not to be regarded as a finished product; on the contrary, it is subject to continual change at present, as it has been throughout its history. Sometimes these changes are sudden, caused by a great earthquake, a volcanic eruption, or violent hurricane, but much more important are the slow, almost imperceptible changes which are brought about by the atmosphere, running water, etc. These are the more important because they are unceasingly active over the whole surface of the land. Changes in the bed of the deep sea are only those due to subterranean agencies, such as diastrophism, earthquakes, and volcanoes.

The changes through which the earth has passed group themselves naturally into cycles, which have been indefinitely repeated and are still in progress. These cycles are both geographical, as recorded in the topographical features of the land and the seacoasts, and geological, as revealed by the study of the rocks. The topography and drainage of a region go through a course of development with definite stages, which are called youth, maturity, and old age. Because of the extreme slowness of the changes and the brevity of human life, it is not possible to observe these stages successively, but each of them may be found exemplified somewhere at the present time. An intelligent comprehension of existing topographies requires a knowledge of the manner in which the features of the land's surface have been produced, modified, and swept away. The process is often called "land-sculpture," because of the analogy of carving a block of wood or stone into relief.

Age of the Earth. In no part of the science of the earth has there been so great and revolutionary a change as in opinions concerning the earth's antiquity. Throughout the Middle Ages, among European nations, the earth was supposed to be 6,000 years old and it was not until the eighteenth century that the famous French naturalist, Buffon, made the startling suggestion that 80,000 years should be allowed. This was before the science of Geology had come into existence, and the development of that science speedily showed that the earth's age must be reckoned in millions of years. From time to time, additional data made it necessary to increase the estimates, and many attempts to deter-

mine the earth's chronology in years were made, but none of them was satisfactory or convincing; they merely showed that the antiquity of the earth was very great, much greater than the physicists and astronomers were inclined to admit.

Of late, two independent methods have been devised, which seem to promise trustworthy and exact results, though one of these deals only with the latest and shortest division of the earth's history. The first of these methods makes use of the phenomena of radio-activity and especially of the changes brought about in the uranium series. After passing through divers changes, this series ends in lead and it is found that the rate of transformation is constant and cannot be hastened or retarded by changing the temperature, pressure, or other conditions. The proportion of lead to uranium (called the *uranium-lead ratio*) in deep-seated rocks which have solidified by cooling from a molten state, gives an accurate measure of the age of those rocks. This method indicates that about 1,000,000,000 years must have elapsed since the formation of the most ancient known rocks, and perhaps as much more time should be allowed for the antecedent, unrecorded period since our planet began its separate existence.

The second method, devised by the Swedish geologist, Baron de Geer, deals only with the final phase of the Glacial epoch and consists in counting the layers, or *varves*, of clay annually deposited along the retreating ice-front. This method gives consistent figures for the date of the disappearance of the ice in Europe and North America.

Subdivisions of Geology. In order to investigate the structure and history of the earth, which form the subject matter of Geology, it is necessary to make use of all the sciences, psychology alone excepted. Mathematics, astronomy, physics, chemistry, mineralogy, zoölogy, and botany are all indispensably necessary for the solving of geological problems, and that is why geology was so late in coming into existence. The Greek philosophers made certain geological observations and drew inferences from these, but the real beginnings of the science do not go back of the middle of the eighteenth century. This was because no geology was possible until the other sciences, physical and natural, had been so far advanced as to afford the needful foundation.

To bring some degree of order out of the immense mass of detail, it is necessary to adopt some method of classification and arrange-

ment, though any such scheme has the drawback of being more or less arbitrary and artificial. The classification most commonly adopted in this country is as follows:

I. Physical Geology	1. Dynamical Geology 2. Structural (or Tectonic) Geology 3. Physiographical Geology (or Geomorphology)
II. Historical Geology	

I. Physical Geology

1. Dynamical Geology

This deals with the various agencies now in operation upon and within an earth which act to modify and change the outer portion of the crust. The deep interior does not appear to be subject to modification other than that due to isostatic adjustment and secular cooling — this cooling may possibly be offset by the effects of radio-activity. It is the changes at and near the surface that form the subject of dynamical geology. Nothing terrestrial is quite stable or unchangeable, a slow and ceaseless circulation of matter is going on upon and within the earth. For the purposes of this study we may regard the matter of the earth as indestructible and of constant amount. The quantity of matter which reaches us from outer space, in the form of meteorites, is relatively so small that it may be neglected.

The agencies which modify the earth are two general classes: (1) the *Subterranean*, which arise within the earth and are due to its own inherent energy, more particularly to the high temperature which, as we have seen, characterizes its interior. To this class belong diastrophism, volcanic activities, hot springs, earthquakes, and the like. These are all manifestations of the internal heat and, originating within the earth, may or may not reach the surface, to bring about changes there. (2) The *Surface* agencies are all due to the energy derived from the sun and penetrate but a relatively short distance into the crust. The work of the atmosphere, of running water, moving ice, lakes, and the sea, animals and plants, comprises the more important classes of the surface agencies, which operate chiefly upon the land and the sea-coast — the sea-bottom is not affected by them. The work of these agents

may be summed up briefly as the destruction and reconstruction of rock and the transportation of rock-materials.

It is the study of changes now going on upon and within the earth which furnishes the key to an interpretation of the earth's past history, but this method is insufficient to solve all geological problems. Many of the changes which the earth has undergone are such that they have never been observed, either because they took place so slowly, or so far below the surface, that they were beyond the reach of observation, and the causes of the change must be inferred from the result. No man has ever observed the birth of a mountain-range, or has seen beds of solid rock folded and crumpled like so many sheets of paper. Such problems are referable to structural geology.

2. *Structural Geology*

This division, also called *tectonic geology*, or simply *tectonics*, deals with the materials of which the earth is composed and the manner in which they are arranged and also endeavors to explain how that arrangement was brought about, for structural geology is not merely descriptive. The structure and arrangement of great masses of rock must be interpreted by the application of dynamical principles, but the application is not always clear and free from ambiguity. This is because a given structure may often be referred, with equal probability, to different dynamic agents. Hence great differences of opinion arise concerning the explanation of structure in a complicated region. The difficulty is to select, from several possible interpretations, the real and rightful explanation. As in all other provinces of geology, the historical point of view prevails: we endeavor to learn, not only the kind of agencies that produced the changes and the manner in which they operated, but also the successive steps of the operations, the order in which they occurred, and their geological date. In no department of geology are there, at present, so much discussion and speculation as in tectonics. Diastrophism, the mode of origin of mountain ranges, continental drift, and similar questions, are all subject to lively and often heated debates and this, in turn, demonstrates the difficulty and obscurity of these problems. Were the solutions obvious, there could be no such differences of opinion.

3. *Physiographical Geology* (*Geomorphology*)

This department of the subject, variously named by different writers, deals with the surface configuration of the land and the manner in which this configuration, also called *topography*, has been produced. Land areas are the result of many complex and conflicting agencies, chief among which are diastrophism and the eroding or denuding forces. Diastrophism tends, on the whole, to increase the height of the land above sea-level, while the eroding agents are unceasingly at work to wear the land away. Inasmuch as land-elevation is usually discontinuous, interrupted by long periods of rest, geographical cycles occur, each of which passes through the stages of youth, maturity, and old age and are indefinitely repeated. Each of the later cycles of the earth's history has left more or less distinct traces of itself, so that several successive cycles may be detected in the configuration of the land; these traces grow less and less distinct with geological antiquity, until they disappear altogether.

In America this subdivision of geology is most commonly called *Physiography*, a term which has the disadvantage of being used in many different senses; literally, it means a description of nature and is thus very vague. Much the best term that has been proposed is *Geomorphogeny*, the genesis of land-forms, but established usage cannot be easily changed.

Dynamical, structural, and physiographical geology together constitute the division of *Physical Geology*, in which the methods are those of the physical sciences, zoölogy and botany being almost excluded, though these have some importance in dynamics. Nevertheless, tectonics and physiography have a large historical element, so that the distinction from historical geology is somewhat vague. Dynamics, on the other hand, deals exclusively with the present — it is the study of processes and results now going on.

II. Historical Geology

Historical geology is the study of the earth's history, including the development of the animals and plants which have lived upon its surface. This history is recorded almost entirely in the stratified rocks (see p. 19), those which have been formed chiefly under water, though also, to some extent, upon the land. It is only such rocks as contain fossils, the remains of animals and plants,

which enable us to determine the chronological succession of the rocks and to correlate the rocks of distant regions and separate continents, so as to construct the history of the earth, which it is the particular aim of geology to write.

The problem of the earth's origin cannot be treated except as part of the solar system, and thus belongs to astronomy. The most ancient known rocks must be much later than the primordial crust of the earth which, it is believed, was formed by the solidification from cooling of the molten mass. Historical geology properly begins with the oldest rocks, the pre-historic portion must be assigned to astronomy.

It has been pointed out that geology calls upon all the sciences, physical and natural, to elucidate the structure and history of the earth and much of its area is common to other divisions. Physical geography and dynamical geology, for example, cover nearly the same ground, and much of mineralogy is required in the study of rocks. Rocks are the particular domain of the geologist, which he shares with no other science, but, as said above, he must have the help of the other sciences in order to understand the rocks. Any considerable constituent of the earth's crust is called a *rock* in geology; this usage differs somewhat from that of vernacular speech, in which the term implies a certain degree of consolidation and hardness. Geologically, a bed of sand, or gravel, or soft clay is as much a rock as granite or marble.

Rocks are composed of *minerals* in a state of mechanical mixture; some few rocks are made up of a single mineral, as, for instance, a very pure limestone; but nearly always several minerals, sometimes a large number, are mixed together to form a rock.

Rocks have no definite chemical composition, or physical properties, or crystalline form. They are composed of granular or coarser aggregates of mineral particles, which may be mixed in any proportions, and the properties of a rock are determined by the proportional amounts of its component minerals. The *rock-forming minerals* are a few common kinds, which occur in great quantities; most minerals are comparatively rare. Thus, rocks shade into one another by imperceptible gradations, while minerals are perfectly distinct and definite, as much so as the species of animals and plants. By analogy, the terms used in the classification of living beings, such as species and variety, are also applied to minerals.

The classification of rocks is, so far as possible, *genetic, i.e.*, according to their mode of origin and formation and, in making this arrangement, only such divisions are to be adopted as may actually be observed in natural processes, or may be experimentally produced. From the genetic point of view, there are two main classes of rocks, the igneous and the sedimentary, while a third, the metamorphic class, is intermediate between the two principal groups.

1. *Igneous Rocks* are those which have solidified by cooling from a molten state; they are found in more or less irregular masses, not divided into layers or beds. A few igneous rocks solidified so rapidly that crystallization was impossible; but, in the great majority of examples, the component minerals are crystalline particles or grains and are, for the most part, of complex chemical composition. The igneous rocks, while still melted and more or less fluid, have been forced upward from the earth's interior and have thus penetrated the overlying rocks in varying ways. Sometimes they reach the surface and are ejected in volcanic masses; more frequently, they solidify at all depths below the surface and in such cavities as they find or make in the preëxisting rocks, through which they have forced their way.

2. *Sedimentary* or *Stratified Rocks* were laid down either under water or, much less frequently, on land, in successive beds or strata. The material of which the sedimentary rocks are made was derived from the disintegration or chemical decomposition of older rocks, was transported by wind or running water, often for very long distances, and was finally deposited, usually in the sea and in horizontal beds. The material of sedimentary rocks is, with a few exceptions, fragmentary, *i.e.*, made up of fragments of all sizes, derived from older rocks and usually rounded and water worn. The component minerals are such as arise from the decomposition of the minerals of the igneous rocks and are therefore simpler in chemical constitution and more stable under conditions which obtain at and near the earth's surface. While the more abundant sedimentary rocks, such as shales and sandstones, are made up of the débris of older rocks, there is an important group, such as limestone, which are accumulations of the shells and tests of animals and plants. A much less important group is made by deposits of lime or flint compounds from solution in water; these are of very limited extent and made by springs.

As the sedimentary rocks are made by the settling of their component fragments, mostly under water, they are laid down in horizontal beds, or strata, though, under exceptional conditions, there are local departures from horizontality. When, therefore, the strata are found, as they very frequently are, in tilted, inclined, or folded attitudes, it follows that they have been greatly disturbed from their original positions.

3. A third class, the *Metamorphic Rocks,* are sedimentary or igneous rocks, which have been more or less reconstructed *in place,* without decomposition or disintegration, but with an increase of hardness. This alteration occurs in all degrees of intensity and completeness, from a simple increase of hardness to a profound reconstruction, with the genesis of entirely new minerals. Thus a sedimentary rock may undergo such radical reconstruction as to become crystalline in texture, its component minerals being those of the igneous class. While there is much that is obscure about metamorphism, it is certain that the principal agent of change is heat.

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CHAPTER II

THE ROCK-FORMING MINERALS

"Although many thousands of compounds are known to chemists, and an almost infinite number are possible, they reduce on analysis to a small group of substances which are called elements. All the compounds found in the earth are formed by their union, *i.e.*, of the elements, with one another, and they are not to any considerable extent reducible to simpler forms of matter by any means now within our control." (F. W. Clarke.) Of these simple undecomposable substances, or rather of these elementary unreducible substances, of which 84 have been definitely discovered and named, only 16 enter very largely into the composition of the earth's crust. The others are rare in that portion of the earth which is accessible to direct examination. It is estimated that 98 per cent of the earth's crust, including the ocean and the atmosphere, is made up of the following eight elements, arranged in order of abundance, with percentages as calculated by Clarke and Washington:

Oxygen (O)	46.68	Calcium (Ca)	3.63
Silicon (Si)	27.60	Sodium (Na)	2.72
Aluminium (Al)	8.05	Potassium (K)	2.56
Iron (Fe)	5.03	Magnesium (Mg)	2.07

The other eight elements in order of abundance, Titanium (Ti), Phosphorus (P), Carbon (C), Hydrogen (H), Manganese (Mn), Sulphur (S), Chlorine (Cl), and Barium (Ba), are present in much smaller quantities, and together form only 1.55 per cent of the earth's crust. Thus 99.89 per cent of the known crust of the earth is composed of only 16 elements, leaving slightly over one-tenth of one per cent for all the others, including such well-known metals as copper, lead, zinc, tin, silver, and gold. Of the 16 elements named, other than gases, only two, carbon and sulphur, occur in nature uncompounded. All the others exist in compounds formed by the union of two or more of them. The elements abundant in the lithosphere are the lighter ones, with atomic weight not exceeding 56, and for the most part much below that. The heavy

metals are found in very small quantities. The deep interior, as shown on page 21, is much denser than the lithosphere, and must contain a far larger proportion of the elements with high atomic weight; but the lighter elements must preponderate over the heavier in the globe as a whole, for a mixture of all the elements in equal proportions would be denser than the earth actually is. The naturally occurring elements or compounds are called minerals, which may thus be defined:

A mineral is a natural inorganic substance which has a homogeneous structure, definite chemical composition, and physical properties and, usually, a definite crystal form. The definite chemical composition is expressed in a formula which gives the number and proportion of the elements uniting to form the compound, but sometimes it is necessary to write the formula in a generalized way. Thus, certain elements and compounds may replace one another without changing the character of the mineral or its form. Such replacement is called *isomorphism* and occurs only with related elements; they are usually, though not invariably, alike chemically. In simple compounds such as chlorides or sulphides, lithium, potassium, cæsium, and rubidium are isomorphous; but sodium is isomorphous with these only in some complex silicates. Chlorine, iodine, and bromine are isomorphous for simple compounds. Calcium, magnesium, manganese, and ferrous iron are isomorphous in many minerals, as are also ferric iron and aluminium. Isomorphism in the highly complex minerals may involve whole groups of elements; and hence the formula of garnet, for example, is written $R''_3 \cdot R'''_2(SiO_4)_3$, R'' standing for calcium, magnesium, iron, and manganese, and R''' usually for aluminium, iron, chromium, titanium, and manganese.

Many minerals of very variable composition, such as the feldspars, micas, amphiboles, and pyroxenes, are now conceived of as being mixtures of certain definite compounds, as will be more fully set forth in the description of these mineral groups.

The problems of the chemical composition and genesis of the minerals and the igneous rocks are very largely those of physical chemistry, in which not only chemical reactions but also physical conditions, such as temperature and pressure, must be taken into account.

The *isomorphous mixtures* of which certain mineral series are made up will be described in a subsequent section. Very similar,

if not identical, relations are those to which the term *solid solution* has been applied.

Crystals are solids of more or less regular and symmetrical shape, usually bounded by plane surfaces. The number of known crystal forms is very great, and yet they may all be grouped in six systems, which are characterized by the relations of their axes. The *axes* of a crystal are imaginary lines which connect the centers of opposite faces, or opposite edges, or opposite solid angles, and which intersect one another at a point in the interior of the crystal. The *systems of crystal forms* have received many names, the following being those which are most generally used in this country:

I. *Isometric System* (monometric, cubical, regular). In this system the three axes are of equal length and intersect one another at right angles.

II. *Tetragonal System* (dimetric, pyramidal). The axes intersect at right angles, but only the lateral ones are of equal length, and the vertical axis is longer or shorter than the laterals.

III. *Hexagonal System.* Here four axes are employed, three equal lateral axes intersecting at angles of 60°, and a vertical axis perpendicular to the laterals and longer or shorter than they.

IV. *Orthorhombic System* (rhombic, trimetric). The three axes intersect at right angles and are all of different lengths.

V. *Monoclinic System* (monosymmetric, oblique). All three axes are of different lengths; the two laterals intersect at right angles, while the third axis is oblique to one of the laterals.

VI. *Triclinic System* (anorthic, asymmetric). Three axes of unequal length and oblique to one another.

It is important to comprehend the relations which the crystal forms of a given system bear to one another. For example, a regular octahedron may be derived from a cube (both of which are in the Isometric System) by evenly paring off the eight solid angles until the planes thus produced intersect one another, the centers of the cube's faces becoming the apices of the solid angles of the octahedron. Conversely, a cube may be derived from a regular octahedron by symmetrically truncating the solid angles until the planes thus produced intersect. By slicing away the twelve edges of a cube or of a regular octahedron a dodecahedron (twelve-sided figure) will result. These crystal forms are, therefore, so related as to be all derivable one from another, and the relations of their axes remain unchanged; all three forms may be assumed by the

same mineral, and they thus properly belong in the same system. Similar relations may be observed between the crystal forms of the other systems.

It might be supposed that the crystal systems and the relations of their imaginary axes were merely mathematical devices to reach a convenient classification of forms, but such a conclusion would be very erroneous. Crystal form is an expression of the arrangement of atoms, and the physical properties of minerals are closely related to their mathematical figure. It is clear that these physical properties are conditioned by the way in which the atoms are built up into the crystal. Amorphous substances refract light equally in all directions, and are thus called isotropic; but when an amorphous substance crystallizes it takes on the qualities proper to its crystal form. Thus water is isotropic, while the hexagonal crystals of ice are singly refractive in only one direction, and doubly refractive in all others. The same substance may, under different circumstances, crystallize in different systems, and will then display the properties appropriate to each system.

Not only the refractive powers of a crystal, but also its mode of expansion when heated, and its conductivity of heat and electricity, are controlled by the arrangement of atoms which determines its form.

The crystals of the isometric system, which have their three axes of equal length, are singly refractive in all directions (isotropic), expand equally when heated, and conduct heat and electricity equally in all directions. Those of the tetragonal and hexagonal systems, which have one axis longer or shorter than the others, are doubly refractive along the lateral axes, expand equally when heated, and show equal conductivity along these axes. Along the third or principal axis they are singly refractive, display a different conductivity, and when heated expand to a different degree. In the orthorhombic, monoclinic, and triclinic systems, which have all the axes of unequal lengths, the crystals are singly refractive in two directions. They expand unequally, and conduct differently along all their axes.

The optical properties of minerals are most useful in the study of rocks, and with the aid of the polarizing microscope very minute crystals may be identified.

Most inorganic substances which are solid under any circumstances are capable of assuming a crystal form, so that solidifica-

tion is usually by means of crystallization. For the formation of large and regular crystals it is necessary that the process be gradual and that space be given for the individual crystals to grow. Usually crystallization begins at many points simultaneously, and the crystals crowd upon one another, resulting in a mass of more or less irregular crystal grains. The same substance which, when very rapidly solidified from the molten state, forms amorphous glass will, if slowly solidified, form distinct crystals.

Crystallization requires that the atoms be free to move upon one another and thus arrange themselves in a definite order. It may take place either by the deposition of a solid from solution, by cooling from the molten state, or by solidification from vapor. In all cases the size and regularity of the crystals depend upon the time and space allowed for their growth. In a manner not yet understood, amorphous solids like glass may be converted into crystalline aggregates without being remelted. Certain glassy volcanic rocks, though amorphous when first solidified, have gradually become crystalline; and similar changes have been observed in certain artificial glasses of considerable antiquity. This process is called *devitrification*. For this and other reasons the physical chemist regards glass, not as a true solid, but as a "super-cooled liquid."

The actual steps of crystallization may be observed by evaporating with extreme slowness the solution of some crystalline salt under a microscope. The first visible step in the process is the appearance in the clear fluid of innumerable dark points, which rapidly grow until their spherical shape becomes plain. The tiny globules then begin to move about rapidly and arrange themselves in straight lines, which look like so many strings of beads, when the beads suddenly coalesce into straight rods. The rods then arrange themselves into layers, and they build up the crystal so rapidly that it is hardly possible to follow the steps of change. In certain glassy rocks, such as obsidian, which are solidified too quickly to form crystals, the incipient stages of crystals in the form of minute globules and hairlike rods may be detected with a microscope.

Many minerals, especially those which crystallize from solution in water, contain water in chemical combination which may be driven off by heating. The water which is readily removed and at a low temperature is called the *water of crystallization;* that which is removed only at a high temperature, the *water of con-*

stitution, bears an entirely different relation to the molecule * from the loosely held water of crystallization. For instance, the crystals of zinc sulphate contain 7 molecules of water ($ZnSO_4 \cdot 7\ H_2O$), of which 6 are removed at a temperature of 100° C., but to remove the seventh the temperature must be raised to 240°. This last molecule is water of constitution; the other six are water of crystallization. Sometimes the water of crystallization is so loosely held that it is driven off in dry air. Ordinary washing soda when freshly formed is in transparent, colorless crystals which contain 10 molecules of water ($NaCO_3 \cdot 10\ H_2O$), 9 of which are lost in dry air and the crystals crumble into a white powder. This process is known as *efflorescence*. Even some of the igneous minerals, such as the micas and hornblendes which crystallize from molten magma, contain water of constitution; but most minerals formed in this way are *anhydrous;* that is, they contain no water.

Cleavage. Many minerals, even the hardest, split more or less readily in certain fixed directions, producing lustrous faces. In other directions these same minerals break with an irregular fracture. This property of splitting is called *cleavage*, and is uniform in the different crystal forms of the same mineral. It takes place parallel to the actual or possible crystal faces. A rhombohedral crystal of calcite (calcium carbonate, $CaCO_3$), when struck with a hammer, will break into exceedingly minute rhombohedrons; and a cubical crystal of galena (lead sulphide, PbS) breaks into tiny cubes. Indeed, it is difficult to find a particle of galena, however small, that is not cubical. On the other hand, in quartz (SiO_2), cleavage, though perfect, is difficult.

Hardness. The hardness of minerals is a useful means of identifying them. For this purpose they are referred to a scale of hardness, ranging from such soft substances as may be readily scratched with the finger-nail, to the hardest known substance, diamond. The degree of hardness is expressed by the numerical place of the mineral in the scale, and intermediate grades are indicated by fractions. Thus a mineral which is scratched by quartz and scratches orthoclase with equal ease has a hardness of 6.5. The scale is as follows:

1. Talc	6. Orthoclase
2. Gypsum (Selenite)	7. Quartz
3. Calcite	8. Topaz
4. Fluorite (Fluorspar)	9. Sapphire
5. Apatite	10. Diamond

* Physicists are now inclined to doubt the existence of molecules in crystals. The term is here retained as a matter of practical convenience.

Color. The color of minerals is rather a complicated matter, but, like hardness, it is very helpful in identification. The color of opaque minerals is due to reflected light, and is greatly affected by the condition of the surface. To make these conditions uniform, it is customary to examine the mineral for color by finely powdering it, which can most readily be done by drawing the mineral with firm pressure across a plate of hard, unglazed porcelain. On such a plate most minerals make a mark, technically called a *streak*, which is made by a fine powder. Hæmatite (ferric oxide, Fe_2O_3) is of many colors, red, gray, brown, or almost black, but all of these give a red streak. In transparent minerals, the color may be due in part to the chemical composition of the mineral, or may be due to minute quantities of included impurities. When pure, quartz is transparent and colorless; but many and differently colored varieties are known, such as *amethyst*, with color due to manganese, and *rose-quartz* which is colored by lithium. *Chrysoprase* is silica made green by nickel. The green of the *emerald* and some *garnets* is due to chromium. Iron produces a variety of colors, according to its quantity and degree of oxidation — red, brown, yellow, green, and blue. Copper produces blue, green, or red, and many blue minerals are colored by cobalt.

Specific Gravity. The specific gravity of a mineral is its weight compared with that of an equal bulk of water.

Forms and Combinations. A *form* is an assemblage of faces, all of which have similar relations to the axes of the crystal. Two or more forms occurring as a single crystal make up a *combination.* Only forms belonging to the same system can occur in combination, but, even with this limitation, the variety and complexity of crystals are very great. Certain forms occur which may be regarded as developed from other forms by the suppression of one-half or three-quarters of the faces.

Irregularities of growth (distortion) are very common, some faces of a form being larger than others, while certain faces may even be obliterated; but however great the variation, the angle at which corresponding faces meet remains constant for each mineral.

Massive and imperfectly crystallized minerals may consist of grains, needles, fibers, or thin layers (laminæ).

Compound crystals are formed by the joining of simple crystals. When two half-crystals are united along a plane in such a way that their faces and axes do not correspond, they are said to be *twinned.*

When the twinning is repeated along parallel planes, the crystal is a *polysynthetic twin*. It would serve no useful purpose to enumerate other kinds of compound crystals.

Pseudomorphs occur when one mineral assumes the crystal form proper to another. This may take place either by the addition or the removal of certain constituents, or some constituents may be removed and others substituted for them. The entire substance of a mineral may be removed and its place taken, particle by particle, by another substance; and yet the form, and sometimes even the cleavage, of the original substance is retained. The study of pseudomorphs is often of the greatest service in throwing light upon the history of the rocks in which they occur.

Rock-forming Minerals. The number of known minerals is large and constantly increasing as new ones are discovered; but most of these are uncommon, and some are at the same time so rare and so beautiful that they command great prices as gems. Only a few minerals, however, are quantitatively important in the earth's crust. These are called *rock-forming minerals*, because the rocks are aggregations of them. Some rocks are made up almost exclusively of a single mineral. A certain very pure limestone consists almost entirely (99 per cent) of calcite. Most rocks are mixtures of several minerals; and as mixtures are mechanical, they may be made in any proportion, and hence the different varieties of rocks may shade into one another by imperceptible degrees.

ROCK-FORMING MINERALS

A. Minerals Composed of Silica

Next to oxygen, silicon (Si) is by far the most abundant constituent of the earth's crust. It is combined with oxygen to form silica (SiO_2) or enters into the formation of more complex compounds.

1. *Quartz* (SiO_2) is anhydrous silica in a crystalline state, and is the most abundant of minerals, at least in the accessible portions of the earth's crust, forming about 12 per cent of all known igneous rocks. Its crystals belong to the Hexagonal System; and those most frequently found are commonly described as being hexagonal prisms capped by hexagonal pyramids. But more accurately they are "combinations of the plus and minus rhombohedrons and the unit prism. When the two rhombohedrons are

equally developed, the crystals have ... minated by an hexagonal pyramid, but this is not possible in the type in which quartz crystallizes." (A. H. Phillips.) It is insoluble in acids, except hydrofluoric, and only very slowly soluble in boiling caustic alkalies.

While cleaving is difficult, the cleavage is perfect. The mineral is very hard (H = 7), scratching glass easily, and cannot be scratched by a knife; sp. gr. = 2.6.

When pure and symmetrically crystallized, quartz is transparent, colorless, and lustrous, and in this form is called rock crystal. More commonly it is found in dull masses. There are many colored varieties of quartz, some of them used as gems, with tints due to the presence of small quantities of metallic or organic compounds.

2. *Tridymite* has the same composition as quartz (SiO_2) but is hexagonal above 130° C., probably orthorhombic at lower temperatures. The crystals are small, scaly hexagonal tablets. The hardness is the same as in quartz (= 7), but the specific gravity is somewhat less (= 2.28–2.33). Above 800° C., which is the transitional temperature between them, Tridymite is the more stable form of SiO_2; below that point, quartz is the more stable.

3. *Chalcedony* occurs in spheroidal or stalactitic masses composed of more or less concentric shells. The chemical composition is the same as in quartz, but the optical properties are different and the mineral is somewhat lighter. Chalcedony is translucent and waxy in appearance, and occurs in various pale colors. The more brightly colored varieties have received special names, such as carnelian, chrysoprase, and bloodstone.

4. *Flint* and *Chert* are mixtures of anhydrous and hydrated silica, and are found in amorphous masses of neutral or dark colors, and are opaque, or somewhat translucent in thin pieces. They have a dense homogeneous texture, suggestive of horn in appearance, and hence are also called *hornstone*.

B. Silicates

There are several compounds of silicon and oxygen, or silicic acids, which form a very extensive series of compounds with various metallic bases. As rock-forming minerals the silicates are extremely important, especially in the igneous rocks.

*I. The Feldspar * Group*

The feldspars are essentially silicates of alumina (Al_2O_3) and some other base: potash, soda, or lime. *Orthoclase* and *microcline* are potash feldspars ($KAlSi_3O_8$); *albite* is a soda feldspar ($NaAlSi_3O_8$); and *anorthite* a lime feldspar ($CaAl_2Si_2O_8$). By the mixture of these end-members in solid solution, two isomorphous series are formed: the lime-soda series, collectively called *plagioclase;* and the potash-soda series, *anorthoclase.*

The feldspars crystallize in the Monoclinic and the Triclinic Systems, but the forms and angles are much alike in both.

All the feldspars have good cleavage in two directions, the angle being 90° in the monoclinic form and nearly 90° in the triclinic. The sp. gr. varies with composition, but the hardness of all is about 6.

These minerals are normally white, or colorless if transparent; but are found tinted by impurities in pale colors — pink, yellow, brown, gray, or green.

The feldspars are the most abundant of terrestrial minerals, the various forms constituting about 60 per cent of igneous rocks.

1. MONOCLINIC FELDSPARS

Orthoclase is a potash feldspar (K_2O, Al_2O_3, 6 SiO_2 or $KAlSi_3O_8$) though soda may replace some of the potash. Its sp. gr. is 2.57. The crystals form stout prisms, thin tables, or irregular grains and masses. The angle between the two planes of cleavage is 90°, and cleavage is much more perfect in one direction than in the other. As a rule the crystals are twinned. Most orthoclase is white, but frequently is pale yellow, pink, or red. The crystals are usually dull, not transparent, because of the presence of inclusions or because of molecular change after crystallization. Weathering produces turbid crystals, which even under the microscope are hazy. Glassy, transparent varieties of orthoclase are called *adularia* and *sanidine.* Sericite, one of the micas, and kaolin are formed by the decomposition of orthoclase.

* In the second edition of this book the name of these minerals is spelled *felspar*, a spelling which is frequent in England though not in this country. According to the Oxford Dictionary, this spelling is erroneous, and was originally introduced by Kirwan, who misunderstood the derivation of the term.

2. TRICLINIC FELDSPARS

The minerals of this section are grouped together under the comprehensive term *plagioclase*, because of the difficulty of distinguishing them from one another in a thin rock section under the microscope. They are very generally characterized by polysynthetic twinning (see p. 28), which produces fine parallel lines on the basal plane and the corresponding cleavage face. They vary in chemical composition and physical properties from purely sodic albite (Ab) to purely calcic anorthite (An). The following table from Dana and Iddings gives the composition of the various members or the series in terms of albite and anorthite. These mixed minerals are not distinct in chemical composition or physical properties, grading into each other on both sides; and there is not complete agreement among writers as to the arbitrary limits of each kind.

Name	*Composition*	*Specific Gravity*
Albite	Ab_1An_0–Ab_6An_1	2.624–2.645
Oligoclase	Ab_6An_1–Ab_3An_1	2.645–2.659
Andesine	Ab_3An_1–Ab_1An_1	2.659–2.694
Labradorite	Ab_1An_1–Ab_1An_3	2.694–2.728
Bytownite	Ab_1An_3–Ab_1An_6	2.728–2.742
Anorthite	Ab_1An_6–Ab_0An_1	2.742–2.758

It will be observed that in composition there is almost perfect transition from pure albite to pure anorthite, and that the specific gravity increases regularly with the rising proportion of the lime ingredient.

Anorthite is decomposed by hydrochloric acid, labradorite is slightly attacked by it, while the other members of the series are not affected.

Microcline has the chemical composition of orthoclase and plays a similar rôle in the constitution of the rocks, but crystallizes in the triclinic instead of the monoclinic system. It is in every respect very like orthoclase, and is often mistaken for it. The bright bluish-green variety is called Amazon stone.

The crystals of the plagioclase feldspars resemble those of orthoclase, except that the angles are different, and they all show the same two distinct cleavages.

Albite is usually pure white, as its name would indicate. The others are normally white, but are often tinted with pink, gray, or other pale colors.

Anorthoclase is the collective name for a series of triclinic potash-soda feldspars. They are of variable composition, and are much less common than orthoclase or the plagioclases.

II. The Feldspathoid Group

These minerals are very closely allied to the feldspars in chemical composition and geological relations, but differ from them in having a smaller proportion of silica, as well as in crystal form and physical properties. They are much less widely distributed than the feldspars, but have nevertheless an important bearing upon the classification of certain rocks in which they occur.

1. *Nepheline* (also called *Nephelite*) is essentially a silicate of sodium and aluminium with the formula $Na_2O \cdot 2\ SiO_2(KAlSiO_4)$, with a little of the potash replaced by soda.

2. *Leucite* is a potassium-aluminium metasilicate $K_2O \cdot Al_2O_3 \cdot 4\ SiO_2\ (KAl(SiO_3)_2)$. It crystallizes in twenty-four-sided figures, trapezohedrons, which are pseudo-isometric, and below the temperature of 500° C it is orthorhombic. In color the mineral is dull white or gray. $H = 5.5–5.6$; Sp. gr. $= 2.44–2.56$. Though leucite is abundant in certain localities and in certain rocks, it is on the whole a rare mineral.

III. The Pyroxene and Amphibole Groups

These two groups contain parallel series of minerals, which are of similar chemical composition but differ in crystallization and in physical properties. Chemically, each group may be divided into two sub-groups, the one of simple and the other of complex composition. The most abundant of the minerals of simple composition are the silicates of magnesium, iron, and calcium, which may crystallize separately or, as a rule, as mixtures of two or all three of these. The complex pyroxenes, or amphiboles, are also, like the simple ones, silicates of magnesium, iron, and calcium; but in addition they contain varying amounts of aluminium, ferric oxide, and, more rarely, other constituents. Some rather rare minerals of both groups contain soda, but none of them contains potash.

The simple pyroxenes and amphiboles crystallize in orthorhombic and monoclinic systems, while the complex minerals of these groups are all monoclinic. Whether orthorhombic or monoclinic, simple or complex, the pyroxenes and amphiboles may be

distinguished from one another by their cleavage. The pyroxenes have a prismatic cleavage of about 90°, and in the amphiboles the angles are 124° 30′ and 55° 30′. The orthorhombic pyroxenes are common, though less so than the monoclinic; but the orthorhombic amphiboles are so rare as to be unimportant as rock-forming minerals, the monoclinic amphiboles being very much more abundant.

The minerals of these groups are very important and abundant and together make up about 17 per cent of all known rocks.

1. ORTHORHOMBIC PYROXENES

Orthorhombic pyroxenes are all simple silicates of magnesium and iron, $MgO \cdot SiO_2$ ($MgSiO_3$) and $FeO \cdot SiO_2$ ($FeSiO_3$), being mixtures of these two in nearly all cases. Different names are given to different parts of the series, as was done in the case of the feldspars.

1. *Enstatite* is the magnesium pyroxene ($MgSiO_3$), with less than 5 per cent of FeO.

2. *Bronzite* contains from 5 per cent to 14 per cent of FeO.

3. *Hypersthene* has more than 14 per cent of FeO, and is the commonest member of the series, of which no purely ferrous member is known.

The color darkens, the specific gravity increases, and the optical properties change with the increase in the percentage of iron. Enstatite is usually gray and has a specific gravity of 3.25; hypersthene is brownish black, and has a specific gravity of 3.4 to 3.5.

2. MONOCLINIC PYROXENES

These are more varied in chemical composition than the orthorhombic minerals of the group.

1. *Diopside* is the most abundant of the chemically simple monoclinic pyroxenes. It is a silicate of calcium and magnesium, $CaO \cdot MgO \cdot 2\,SiO_2$ ($CaMg(SiO_3)_2$). The color is white or light green, and it has a specific gravity of 3.2. Diopside usually has varying degrees of admixture of the simple lime-iron pyroxene Hedenbergite, $CaO \cdot FeO \cdot 2\,SiO_2$ ($CaFe(SiO_3)_2$), which has a specific gravity of 3.5 to 3.6. The mixed crystals are dark brown or green.

2. *Wollastonite* is another less abundant monoclinic pyroxene. It is a silicate of calcium, $CaO \cdot SiO_2$ ($CaSiO_3$), and usually crystal-

lizes in long, white, flat prisms or tables, with a specific gravity of 2.9.

3. *Acmite* is a yellowish sodium-iron pyroxene, $NaO \cdot Fe_2O_3 \cdot 4\ SiO_2$ ($NaFe(SiO_3)_2$). Though rare, acmite is important in the study of rocks.

4. *Augite* is a chemically complex pyroxene, and the most abundant mineral of the group. It is a silicate of calcium, magnesium, and iron, with varying amounts of aluminium and ferric oxide in so-called solid solution according to the latest interpretation. No general formula can be given. Augite is black or very dark green, and crystallizes usually in short, stout prisms. Sp. gr. = 3.2–3.4; H. = 5–6.

Diallage is a variety of augite, usually green in color, and distinguished by its laminated structure and peculiar luster.

5. *Ægirite* is a rather rare, black or dark green, sodium pyroxene, and is a mixture of acmite, diopside, and hedenbergite in varying proportions.

3. MONOCLINIC AMPHIBOLES

The amphiboles are for the most part of more complex chemical composition than the pyroxenes, and their specific gravities are regularly less than those of the corresponding pyroxenes.

1. *Tremolite* is the simple calcium-magnesium amphibole, $CaO \cdot 3\ MgO \cdot 4\ SiO_2$ ($CaMg_3(SiO_3)_4$). The color is gray, white, brown, or nearly black, according to composition, with white or gray streak. It usually forms long, bladed crystals. Sp. gr. = 3.

2. *Actinolite* resembles tremolite, but contains iron as well as magnesium, $CaO \cdot 3(MgFe)O \cdot 4\ SiO_2$ ($Ca(MgFe)_3(SiO_3)_4$). It is dark green in color, and crystallizes in long prisms. Sp. gr. = 3–3.2, according to the proportion of iron.

3. *Hornblende* is the common representative of the chemically complex amphiboles, corresponding to augite among the pyroxenes, and having similar chemical composition. In color it is usually black or dark green or brown. It crystallizes in prisms and has a hardness of 5 to 6 and a specific gravity of 3.1 to 3.3.

IV. The Mica Group

The micas are of such complex and variable chemical composition that it is difficult to give formulas for them. They are all silicates of aluminium and other bases, especially potassium, mag-

nesium, and iron, with lithium and sodium in some rare varieties. All the micas contain water (hydroxyl), but do not contain lime. When distinctly crystallized, the micas form six-sided plates or thick prisms which, though of hexagonal habit, are really monoclinic. The micas possess a perfect cleavage, splitting readily into thin, flexible, and elastic leaves, a character which distinguishes them from all other common minerals. They are quite soft, and most of them may be scratched with the finger nail. There are two main sub-groups, the light-colored alkaline micas and the dark ferro-magnesian micas.

1. *Muscovite* is the most important and widespread of the alkaline micas, and occurs most frequently in granite and gneiss. Its general formula is $K_2O \cdot 2\,H_2O \cdot 3\,Al_2O_3 \cdot 6\,SiO_2$ ($H_2KAl_3(SiO_4)_3$). Muscovite is a lustrous, silvery white mineral, generally transparent and colorless in thin leaves. H = 2–2.5; Sp. gr. = 2.75–3.1.

Other alkaline micas are the pink lithium mica, lepidolite, and the white sodium mica, paragonite; but both of these are very rare. Sericite is a variety of muscovite which forms minute, silvery scales. It is an alteration product and often derived from feldspar.

2. *Biotite* is the commonest of the dark ferro-magnesian micas, and occurs in many granites and similar rocks. It is a highly complex silicate of aluminium, potassium, magnesium, and iron with hydroxyl. There are many varieties, but most of them contain more magnesium than iron. The color is black or very dark green or dark brown even in thin leaves. Specific gravity and hardness are much as in muscovite.

V. The Olivine Group

The minerals of this group are quite important and abundant, though less so than the micas. They stand in much the same relation to the pyroxenes and amphiboles as the feldspathoids do to the feldspars. The common minerals are all of very simple chemical composition, silicates of magnesium and iron, and they form an isomorphic series of mixtures of the two end members, forsterite, $2\,MgO \cdot SiO_2$ (Mg_2SiO_4) and fayalite, $2\,FeO \cdot SiO_2$ (Fe_2SiO_4), analogous to the series of plagioclase feldspars. The mixed members of this series are collectively called olivine, which crystallizes in the orthorhombic system and forms short prisms or irregular grains. The specific gravity varies with the amount of iron from 3 to 4.1,

and the hardness from 6.5 to 7. The color ranges from yellow to olive green, rarely colorless, and the irregular grains look like fragments of bottle glass.

VI. The Garnet Group

The garnets are highly complex orthosilicates with a general formula $R''_3R'''_2(SiO_4)_3$. In these minerals R'' may be calcium, magnesium, ferrous iron, or manganese; and R''' may be aluminium, ferric iron, or chromium, though in most specimens only two or three of these elements are present in any considerable proportion. Various names are given to the different varieties, according as different members of these bases predominate. Garnets crystallize in the isometric system, and the usual forms are the dodecahedron (twelve-sided figure) and the trapezohedron (twenty-four-sided figure). Large and coarse garnets, such as are ordinarily found, are opaque; but the clear and brilliantly colored kinds are extensively used in jewelry as semi-precious stones. The garnets have no cleavage, and their specific gravity varies from 3.2 to 4.3, according to composition, and the hardness is 6.5 to 7.5.

1. *Almondite,* $3\ FeO \cdot Al_2O_3 \cdot 3\ SiO_2$ ($Fe_3Al_2(SiO_4)_3$) is the commonest representative of the group, and is an orthosilicate of iron and aluminium. Transparently clear and red specimens are the semi-precious stone, carbuncle. Garnets are of very many colors. Most of them are red, but they are frequently colorless, white, yellow, orange, brown or green, but blue ones are not known.

2. *Pyrope* is a magnesium-aluminium orthosilicate, $3\ MgO \cdot Al_2O_3 \cdot 3\ SiO_2$ ($Mg_3Al_2(SiO_4)_3$). Clear, dark red crystals form the precious garnet of the jeweler.

VII. The Epidote Group

Epidote is a silicate of calcium and aluminium, often with considerable iron, and always with a little water (hydroxyl). The crystals are monoclinic long prisms, with a good cleavage in one direction. In color the mineral is ash-gray or dark yellowish green; gray when free from iron, and dark yellowish green when iron is present. Sp. gr. = 3.3–3.5; H = 6–7.

An orthorhombic calcium-aluminium epidote is zoisite, which is gray in color and has a specific gravity of 3.3.

C. Other Silicates, Chiefly Alteration Products

Many of the complex silicates, when exposed to the action of the weather or of percolating water, become more or less profoundly changed chemically. The change is known as alteration, and forms an early stage of decay. One of the commonest of these changes is hydration, the taking up of water into chemical union with the mineral; and this may be accompanied by the loss of soluble ingredients, or the replacement of some constituents by others.

I. Talc and Chlorite Groups

1. *Chlorite.* Under this name are grouped several closely allied minerals of complex, uncertain composition; they are probably mixtures of several isomorphic types, but it is not yet definitely known just what those types are. The minerals are all orthosilicates of aluminium and ferrous iron, and usually contain magnesium and are soft minerals, with a hardness of 1 to 1.5 and a specific gravity of 2.6 to 2.96. As indicated by the name, the color is usually some shade of green, though when magnesium is present it may be pink. These minerals crystallize in the monoclinic system with a pseudo-hexagonal symmetry, and are laminated, readily splitting into thin leaves, as do the micas, from which they may be distinguished by the fact that the leaves, though flexible, are not elastic.

The chlorites may result from the alteration or hydration of almost any magnesium mineral which contains aluminium, such as hornblende, augite, or biotite.

2. *Talc* is a hydrated magnesium metasilicate, $3\ MgO \cdot 4\ SiO_2 \cdot H_2O$ ($H_2Mg_3(SiO_3)_4$). The water varies in amount, and may be as much as 7 per cent. H = 1; Sp. gr. = 2.56–2.8. Talc is white or pale green in color, with a pearly luster and a greasy, soapy feeling to the touch. It is rarely found in well-formed crystals; but when they do occur, these have a false hexagonal symmetry, and it is doubtful whether they should be referred to the orthorhombic or to the monoclinic system. Usually the mineral is found in flakes or foliated masses, which split into thin, non-elastic leaves. It results from the alteration of magnesian minerals.

3. *Serpentine* is a hydrated silicate of magnesium and iron, $3(MgFe)O \cdot 2\ SiO_2 \cdot 2\ H_2O$ ($H_4Mg_3Si_2O_9$). Distinct crystals occur only as pseudomorphs. Sp. gr. = 2.5–2.65; H = 2.5–4. The

proper color is green, but it is commonly mottled with red or yellow by iron stains. Serpentine is usually formed by the alteration of olivine, and is less commonly derived from augite or hornblende.

4. *Kaolinite*, or clay, is a hydrated aluminium orthosilicate, $Al_2O_3 \cdot 2\,SiO_2 \cdot 2\,H_2O (H_4Al_2Si_2O_9)$. It is usually soft and plastic, but orthorhombic crystals of pseudo-hexagonal symmetry may sometimes be detected with a microscope. Kaolinite is derived from the decomposition of the feldspars, especially of those kinds which are alkaline in composition.

5. *Glauconite* is a hydrated silicate of iron and potassium, with small quantities of aluminium, calcium, magnesium, and sodium. It is soft and friable, without crystalline form, and in color is of various shades of green.

II. Zeolite Group

This group includes a large number of minerals, all of which are hydrated silicates of aluminium, with calcium, or the alkalies, or both, and little or no magnesium. They do not occur as primary minerals, but are formed by the hydration of such minerals as the feldspars and feldspathoids. They are common in igneous rocks, in which they often fill cavities by deposition from solution. Before the blow-pipe, they all boil and effervesce, because of the abundant water which they contain.

D. Calcareous and Magnesian Minerals

1. *Calcite*, calcium carbonate, $CaCO_3$, Sp. gr. = 2.72; H = 3. This mineral crystallizes in the hexagonal system, in a great variety of forms; rhombohedrons and scalenohedrons are common, hexagonal prisms and pyramids less so. Of the three hundred thirty recognized forms of this mineral, only a very few are important as rock-forming. Cleavage is very perfect, parallel to the faces of a rhombohedron. The mineral is rapidly decomposed even by cold, dilute acids, with effervescing escape of CO_2. When pure, calcite is colorless, brilliantly transparent, and strongly doubly-refractive; more commonly it is white and opaque. It is readily soluble in water containing CO_2, forming the bicarbonate, which is present in solution in nearly all natural waters; in varying degrees of purity calcite makes up the great masses of limestone.

2. *Aragonite* ($CaCO_3$) has the same chemical composition as calcite, but is somewhat heavier and harder. Sp. gr. = 2.93;

H = 3.5–4 and crystallizes in the orthorhombic system. It has not the strongly marked cleavage of calcite and is less stable; when heated, it falls into tiny rhombohedrons of calcite.

3. *Gypsum*, hydrated calcium sulphate, $CaSO_4 \cdot 2H_2O$, Sp. gr. = 2.31–2.33; H = 1.5–2; it crystallizes in tabular forms belonging to the monoclinic system, and cleaves into thin, brittle, and non-elastic leaves. When colorless, transparent, and crystalline, it is called *Selenite*, but usually occurs in large, granular, white masses, which are extensively quarried or mined for *Plaster of Paris*. This is made by heating the gypsum until the water is expelled. *Alabaster*, in the modern sense of that term, is a firm, very fine-grained gypsum, which is white or mottled in pale colors.

4. *Anhydrite* is calcium sulphate without water, $CaSO_4$; it is harder and heavier than gypsum (Sp. gr. = 2.9–2.98; H = 3–3.5) and crystallizes in the orthorhombic system. The crystals have three sets of cleavage planes which intersect one another at right angles.

5. *Apatite* is calcium phosphate and chloride or fluoride, $Ca_4(Ca(F, Cl))(PO_4)_3$. Sp.gr. = 2.92–3.25; H = 5. It crystallizes in hexagonal prisms, capped by hexagonal pyramids, and also occurs massive. Apatite is sometimes transparent and colorless, but is more commonly opaque brown or green; it is soluble in acids and in water containing carbon dioxide or ammonia.

6. *Fluorite*, calcium fluoride, CaF_2, Sp. gr. = 3.01–3.25; H = 4; crystallizes in the isometric system, usually in cubes, and has a perfect octahedral cleavage. Fluorite, when pure, is either transparent and colorless or forms beautiful crystals of blue, green, yellow, or brown. Common name is *fluor spar*.

7. *Dolomite*, calcium and magnesium carbonate, $(CaMg)CO_3$, resembles calcite in appearance and crystallizes in rhombohedrons which often have curved faces. Sp. gr. = 2.8–2.9; H = 3.5–4. Dolomite may be readily distinguished from calcite by the fact that cold, dilute acids have but little effect upon it.

8. *Magnesite*, magnesium carbonate, $MgCO_3$, crystallizes in the hexagonal system, but crystals are rare and the mineral usually occurs in white or gray masses.

ORE MINERALS

Of the six metals listed on page 21 as forming considerable proportions of the earth's crust, only two, aluminium and iron, are

extensively made use of in the metallic state, and their compounds are both rock-forming and ore-forming minerals. So very great is the economic importance of the metals that Chapter XXIII is devoted to a description of ore deposits, and some account of the commoner minerals of which the ore-bodies are composed is required. The ore minerals are of two classes, primary and secondary. The first are those originally deposited, and these are mostly simple compounds, oxides and sulphides. The secondary class are those which have been chemically changed since their first deposition, sometimes dissolved and redeposited, and these, besides secondary sulphides and native metals, are mostly hydrates and carbonates, formed by the action of water and CO_2.

A. Oxides

1. *Hæmatite*, or Specular Iron, is ferric oxide, Fe_2O_3, Sp. gr. 4.5–5.3; H = 6.5. It crystallizes in rhombohedrons, but is usually found in nodular masses. The color is black, steel-gray, or red, and is always red in fine powder.

2. *Limonite*, or Brown Hæmatite, a hydroxide of iron, exists in many varieties, according to the proportion of combined water. The varieties are colloids and have no constant composition except *Gœthite*, $FeO(OH)$, which crystallizes in the orthorhombic system. These are all secondary minerals, due to weathering, and often deposited from a solution of ferrous carbonate or formed from the oxidation and hydration of iron sulphides.

3. *Magnetite* is the black oxide of iron, Fe_3O_4 or $Fe(FeO_2)_2$, Sp. gr. = 4.9–5.2; H = 5.5–6.5. Crystals are isometric, usually octahedrons, sometimes dodecahedrons. The mineral is strongly magnetic, forming the natural lodestone, from which magnetism was first discovered; it is black in color with a bluish-black metallic luster in reflected light. Magnetite is very widely diffused among igneous rocks, and some important ore-deposits are segregated from magmas, especially of the more basic kinds. It also occurs in veins and beds, a valuable source of the supply of iron.

4. *Ilmenite* is an oxide of iron and titanium, $FeTiO_3$. Sp. gr. = 4.5–5.2; H = 5–6. Rhombohedral, when crystallized, but is usually massive. Titaniferous iron ores are much more difficult to smelt than the ores which are free from titanium, but they are valuable for certain purposes, such as making tool-steel.

5. *Chromite*, iron and chromium oxide, $FeCr_2O_4$, crystallizes in octahedrons, or is massive. Sp. gr. = 4.32–4.57; H = 5.5. The mineral is gray or black in color and usually has a metallic luster. It occurs in association with ultrabasic igneous rocks, such as peridotite, and is found in astonishing quantities in South Africa. The metal chromium, which is much like nickel in character and uses, is all derived from this ore.

6. *Cassiterite*, dioxide of tin, SnO_2, crystallizes in the tetragonal system, as short prisms terminated by pyramids. Sp. gr. = 6.8–7.1; H = 6.7. The color is dark, gray to black, and lustrous. This, almost the only important ore of tin, is found in granite and especially in pegmatite.

7. *Franklinite*, oxide of iron, manganese, and zinc $(FeMnZn)(FeMn)_2 \cdot O_4$. Crystals of isometric system, commonly octahedrons. Sp. gr. = 5.07–5.28; H = 5.5–6.5. In northern New Jersey, at Franklin Furnace and Stirling Hill, franklinite is an important source of zinc, but is not known elsewhere in commercial quantities.

8. *Pyrolusite*, or manganese dioxide, MnO_2, is amorphous and is found as massive or fibrous deposits. The mineral is secondary and is concentrated in solutions from the decomposition of silicates which carry the metal.

9. *Bauxite*, hydrated aluminium oxide, $Al_2O_3 \cdot 2\,H_2O$, is likewise a secondary mineral, derived from the decomposition of silicates, especially of feldspars. It is amorphous, without crystalline form, and occurs in extensive, clay-like deposits, and, unless stained yellow or red by iron, is white or gray. Sp. gr. = 2.4–2.55; H = 1–3. At present bauxite is the only ore used for smelting aluminium, as extraction from clay is much too difficult and costly for commercial purposes.

10. *Cuprite*, red cuprous oxide, Cu_2O, forms isometric crystals, octahedrons, dodecahedrons, or cubes. Sp. gr. = 5.85–6.15; H = 3.5–4. Cuprite occurs in massive and granular as well as crystallized form, is a regular accompaniment of copper deposits, and an important ore; it is derived from the oxidation of copper sulphides and is therefore secondary.

11. *Zincite*, ZnO, is a secondary zinc oxide; only at Franklin and Stirling Hill, New Jersey, is it found in commercial quantities.

B. Sulphides

Most sulphides are primary and form the most productive ores of copper, lead, zinc, and mercury; some silver is obtained from the sulphide and the iron-sulphur compounds are very important economically, but not as a source of the metal. Many of the valuable ores are compounds of sulphur with two or more metals.

1. *Argentite*, or silver sulphide, Ag_2S, occurs in octahedral and other crystal forms of the isometric system. Sp. gr. = 7.2–7.35; H = 2–2.5. Its color is dark gray with metallic luster.

2. *Galena* is lead sulphide, PbS; crystallizes in the isometric system, usually in cubes or in combinations of cube and octahedron. Sp. gr. = 7.4–7.6; H = 2.5–2.75. Galena is the principal source of lead and is isomorphous with argentite, thus very frequently containing silver. A considerable share of the annual production of silver is derived from the smelting of lead-ores.

3. *Sphalerite*, a sulphide of zinc, ZnS, is the principal ore of zinc; its complex, combination crystals are of the isometric system and its color, white when pure, is generally made dark by small admixtures of iron or manganese. Sp. gr. = 3.9–4.1; H = 3.5–4.

4. *Cinnabar*, the only ore of mercury, is the sulphide, HgS. It is a very heavy, usually massive, red to ruddy-brown mineral, of which the rare crystals are rhombohedrons. When powdered, cinnabar is vermilion to scarlet in color. Sp. gr. = 8–8.2; H = 2–2.5.

5. *Chalcocite*, cuprous sulphide, CuS, is a secondary sulphide, occurring in association with nearly all copper deposits and sometimes, as at Butte, Montana, it is the principal ore. The tabular crystals are of the orthorhombic system. Sp. gr. = 5.5–5.8; H = 2.5–3.

6. *Pyrite*, or Iron Pyrites, is a bisulphide of iron, FeS_2. Sp. gr. = 4.9–5.2; H = 6.5. Crystallizes in the isometric system, usually as cubes, sometimes as dodecahedrons, and has a very characteristic brassy color and luster, to which it owes its popular name of "fools' gold," but often the fools are justified, for not seldom pyrite carries gold in profitable quantity and is then said to be auriferous. Pyrite is very hard and will strike fire with steel, to which it owes its German name of *Eisenkies*, or iron flint. The mineral is very widely disseminated in all classes of rocks.

7. *Marcasite*, White Iron Pyrites, has the same composition as

pyrite, FeS_2, but crystallizes in modified prisms of the orthorhombic system, and more commonly occurs in nodular masses with a radial structure. It has the same hardness as pyrite, but is not quite so heavy. Sp. gr. = 4.68–4.85. Its color is paler than that of pyrite, but may be black. It decomposes readily and after a few months' exposure, indoors, often crumbles to a whitish powder.

8. *Pyrrhotite,* magnetic sulphide of iron; formula usually given is Fe_nS_{n+1}, commonly $Fe_{11}S_{12}$, but varies from Fe_5S_6 to $Fe_{16}S_{17}$. The mineral is massive; when crystals occur, which is seldom, they are tabular and six-sided, belonging to the hexagonal system. Color is a bronze yellow. Sp. gr. = 4.58–4.64; H = 3.5–4.5.

9. *Pentlandite.* Nickel is present in pyrrhotite in varying quantities, and pentlandite is the name given when the proportion of nickel is 6 per cent or more.

10. *Chalcopyrite,* or Copper Pyrites, $CuFeS_2$, appearance brassy, like pyrite, but crystallizes in the tetragonal system. Sp. gr. = 4.1–4.3; H = 3.5–4. This is one of the most abundant of copper ores.

11. *Bornite* is also a sulphide of copper and iron, but in different proportions, Cu_3FeS_3, the greater percentage of copper giving the mineral a metallic, copper-red appearance. The very rare crystals are of the isometric system. Sp. gr. = 4.9–5.4; H = 3. Chalcopyrite, chalcosite, and bornite, all sulphides, are the most important ores of the metal.

12. *Stannite* is the sulphide of copper, iron, and tin, Cu_2FeSnS_4; when crystalline, it is of the tetragonal system. Sp. gr. = 4.3–4.52; H = 4. The mineral is an ore of tin, but is rather uncommon and, therefore, of secondary importance.

C. Carbonates

Carbonate ores are nearly all secondary and due to weathering of the oxides and sulphides, but siderite is often syngenetic in sedimentary rocks.

1. *Siderite* is ferrous carbonate, $FeCO_3$. Sp. gr. = 3.7–3.9; H = 3.5–4.5. Crystallizes in rhombohedrons, which often have strongly curved faces. When fresh, the color is gray or brown. It is but slightly attacked by cold acids, but hot acids dissolve it with effervescence. Siderite is a valuable ore, especially when mixed with clay, when it is called clay iron-stone.

2. *Malachite,* the basic carbonate of copper, $(CuOH)_2CO_3$, occurs in nodular masses of a beautiful green color; the rare crystals are monoclinic. Sp. gr. = 3.9–4; H = 3.5–4.

3. *Azurite* is also a copper carbonate, $Cu(OH)_2 \cdot 2\,(CuCO_3)$, of a deep blue color; the monoclinic crystals are less rare than those of malachite. Sp. gr. = 3.77–3.84; H = 3.5–4.

4. *Cerussite* is lead carbonate, $PbCO_3$; crystallizes in the orthorhombic system, in tabular, prismatic, or pyramidal forms. Sp. gr. = 6.46; H = 3–3.5. Color gray, yellow, or white. Cerussite is produced by the weathering of galena and is an important ore.

5. *Smithsonite* is the secondary carbonate of zinc, $ZnCO_3$, which forms in zinc deposits by weathering of the sulphides. It occurs in masses which are white when pure, but are often stained yellow, brown, or green. Crystals hexagonal. Sp. gr. = 4.3–4.45; H = 5.

D. Silicates

The only silicate ores of economic importance are those of zinc.

1. *Willemite* is a silicate of zinc, Zn_2SiO_4, which is commercially important only at Franklin, New Jersey, that highly remarkable ore-body. It is usually massive and green, yellow, brown, or red in color. Crystals, when formed, are hexagonal. Sp. gr. = 3.89; H = 5.5.

2. *Calamine* is hydrated zinc silicate, $Zn_2SiO_4 \cdot H_2O$, formed by weathering. Crystals orthorhombic. Sp. gr. = 3.4–3.5; H = 4.5–5.

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CHAPTER III

THE IGNEOUS ROCKS

The igneous rocks are those which have solidified from a state of fusion; they are of subterranean origin and have either forced their way upward to the surface or have cooled and solidified at various depths beneath it. The term *igneous*, from the Latin *ignis*, fire, is a misnomer, for there is no fire involved; it should be understood to mean high temperature. Although it is extremely probable that the rocks of this class were the first to be formed on the earth, it does not follow that all igneous rocks must be geologically ancient. On the contrary, they have been formed, in the sense of consolidated, throughout the recorded history of the earth and, as volcanoes demonstrate, are forming now. They are thus the primary rocks and all the others have been derived from them, directly or indirectly. The sedimentary rocks were formed, at least initially, out of the material derived from the chemical decomposition or mechanical disintegration of the igneous rocks.

The igneous rocks are massive, as distinguished from stratified, though they may occasionally display a deceptive appearance of stratification, due sometimes to the piling of lava flows upon one another, or to platy jointing or to flow structure. Like all other consolidated rocks, those of the igneous class are divided by joints into blocks of great variety of size, shape, and regularity. In some rare instances the joint-blocks are plate-like or slab-like, and so imitate stratification, but the deception may easily be understood. The term *massive* is often employed as a synonym of igneous or unstratified.

Magma, derived from the Greek μάγμα, or dough, is the name given to an igneous mass while still in a molten or fused condition. From theoretical considerations, it may be inferred that a magma which is solid from pressure may be potentially liquid and become fused by release of pressure, without increment of temperature, but, of course, no one ever saw magma in any such condition.

There are characteristic differences between those igneous masses which have cooled and solidified deep within the earth, and, therefore, with extreme slowness, and those which have solidified at or very near the surface. The former are called *plutonic* (or abyssal, or intrusive) and the latter *volcanic* (or extrusive); between the two kinds every transition may be found and the term *hypabyssal* is employed for masses cooled at moderate depths and intermediate in character between the typically plutonic and the volcanic. Plutonic bodies often occur at the surface

FIG. 1. — Obsidian, nearly natural size, showing glassy luster and fracture.

of the ground, but that is because the overlying cover of rocks has been stripped away by denudation. Often it may be demonstrated that thousands of feet of overlying strata have been removed in this manner to expose the plutonic mass.

Texture. The texture of an igneous rock is the term employed to indicate the shape, relative size, and mode of aggregation of the constituent mineral particles and is a very important means of determining the conditions under which the rock was solidified. It registers so accurately the circumstances of solidification, the rate of cooling, pressure, relative content of gases and vapors, etc., that all the varieties shade into one another by imperceptible

gradations and form a continuous series. Nevertheless, it is necessary to distinguish and name the more significant kinds of texture, which are five in number, with several minor varieties.

1. *Glassy.* Here the rock is a glass, or slag, without distinct minerals in it, though the incipient stages of crystallization, such as minute globules and hair-like rods, are often to be seen with the microscope.

2. *Compact* or *Felsitic* texture is characterized by the formation of exceedingly minute crystals, too small to be identified by the naked eye, which give the rock a "matt," stony appearance, without the luster of the volcanic glasses. If the crystals are too minute for minerals to be identified even with the aid of the microscope, the rock is said to be *cryptocrystalline*, but if they are identifiable microscopically, the rock is called *microcrystalline*.

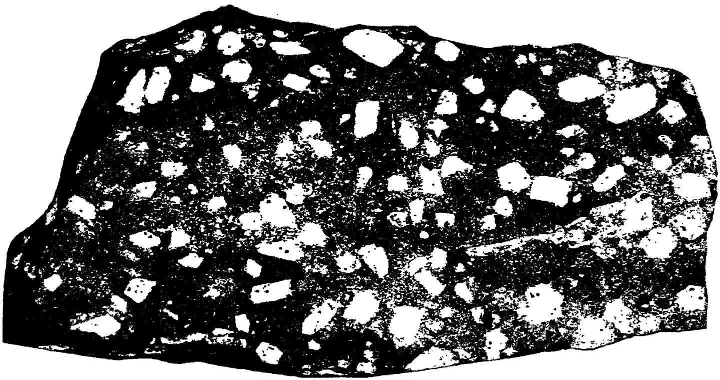

FIG. 2. — Porphyry, nearly natural size, showing phenocrysts of feldspar.

3. *Porphyritic.* In rocks of this texture are large, isolated crystals, called *phenocrysts*, scattered through a ground mass, which may be a glass, or composed of minute crystals; the phenocrysts may have sharp edges and well-formed faces, or they may be corroded and somewhat irregular. This texture indicates two phases of crystallization; first, the formation of the phenocrysts, which remain suspended in the magma and are often corroded,

or partially redissolved, or resorbed by it. These crystals in lavas are said to be of *intratelluric* origin, because formed before extrusion of the magma, and several active volcanoes of the present-day shower out large, well-formed crystals. Stromboli, for example, yields numerous crystals of augite. There is, however, reason to believe that sometimes the phenocrysts are not formed until after the extrusion of the containing lava. The second phase of porphyritic solidification consists in the formation of the ground mass, which may be glassy or finely crystalline, or both. Mineral particles which have a distinct crystalline form are said to be *idiomorphic.*

4. *Granitoid.* In this texture, the rock is completely crystalline, without ground-mass or interstitial paste. The grains of the rock, which may be quite fine or very coarse, are of quite uniform size, and as the crystals have interfered with one another in the process of formation, they have rarely acquired their proper crystalline shape. Such irregular grains are said to be *allotriomorphic.*

Another classification of textures which is now widely used is as follows:

I. *Phaneritic,* or *Grained,* Rocks. In this class the constituent mineral particles are so distinct that they may be recognized by the unaided eye, or with the help of a hand-lens. The class includes the uniform, even-grained rocks, such as granite, and the porphyries and pegmatites.

II. *Aphanitic* rocks are stony and dull, not lustrous, in appearance, but the mineral particles are too minute to be seen except with the microscope. This class is the equivalent of the compact or felsitic texture in the other scheme.

III. Glassy rocks have already been defined.

It will be observed that the difference between these two methods of classification are in the terms; the underlying conceptions are the same in both plans.

The glassy and compact textures are characteristic of lavas, such as are poured out on the surface of the ground, — volcanic rocks, in short. The plutonic rocks have no glass, except sometimes, when the surface of a plutonic body has been suddenly chilled by contact with the country rock. In such a case, the glass is merely a surface film; there is none within the rock. The typical plutonic texture is the granitoid, but porphyries occur in

both classes, and then the difference is in the ground mass, the phenocrysts being much alike in both. In a porphyritic lava the ground mass is glassy or very finely crystalline, while in a plutonic porphyry it is entirely, and more coarsely, crystalline. The hypabyssal rocks, which are intermediate between the volcanic and the plutonic rocks in position, are also intermediate in texture.

The *structure* of an igneous rock means the arrangement of its elements. Thus, in a granite, for example, the mineral constituents are irregularly arranged, with no segregation of any of them, and the structure is said to be mixed. In a gneissic granite, on the other hand, the rock is plainly banded, the dark mineral, hornblende, or mica, being arranged in parallel plates. This is called *flow-structure*. Another type of structure is that produced by the quantity and arrangement of the bubble holes caused by the volatile constituents, the gases, and vapors of the magma. When the solidifying mass is made frothy by these bubbles, the structure is said to be *pumiceous* or *scoriaceous*. Pumice is a glass, so frothy that it floats, until water penetrates the cavities and the mass becomes water-logged and sinks. The surface of a lava-flow is covered with cindery, slaggy pieces, too heavy to float and yet surprisingly light and as porous as bread. These structures are found only in volcanic rocks and can be formed only at atmospheric pressures. The *vesicular* structure has the bubbles in much smaller quantity and of more or less ovoidal shape, owing to the slow movement of the lava, which has elongated the spherical holes into almond-shaped cavities. Often the cavities are filled with minerals, most commonly zeolites, which are deposited from solution in percolating waters. The structure is then said to be *amygdaloid*, from the Greek word for almond.

Pumiceous and scoriaceous structures are exclusively volcanic. Vesicular structure is characteristic of the deeper part of lava-flows, often ceasing abruptly at a certain plane, which marks the level at which the volatile substances all escaped, while the lava was still too completely fluid to retain gas cavities. Some hypabyssal rocks show vesicles, and a comparable structure, called *miarolitic*, occurs often in granites. The term, taken from an Italian name, *miarolo*, for the Baveno granite, applies to small holes due to contraction in crystallization, in which mineralizers gather and perhaps enlarge the holes, depositing well-formed crystals in the cavities, of the same minerals as in the body of the rock.

The *fragmental* structure is caused by explosions of vapors and gases within a volcano, which hurl fragments of the magma into the air and often to the height of several miles. The fragments are of all possible sizes, from great blocks weighing many tons down to the most impalpable dust. *Volcanic ash*, so called from its appearance, is made up of minute fragments of glass, crystals, and lava, and is transported by strong winds for hundreds of miles and deposited, often in a state of remarkable purity. The fragmental textures are entirely volcanic and yet the rocks are not exactly igneous, for the finer materials, transported and deposited by wind or water, mingled in all proportions with ordinary sedimentary material, make rocks of which the material is more or less igneous, the mode of formation sedimentary. Hence, they are called *pyroclastic* rocks, which is a Greek form of the Latin *igneo-fragmental*.

Consolidation. The solidification of magma into rock is an extremely complicated process which is by no means thoroughly understood, and concerning which, therefore, there is much difference of opinion among petrologists. It is generally agreed that a thoroughly fused magma is not made up of dissociated oxides, but is a mixture of silicate compounds and others in mutual solution. The glassy rocks, which have solidified (so far as they can be called solid) so rapidly that crystallization could not begin, give a true picture of the magma, so far as composition is concerned, minus the gases and vapors, which mostly escaped in solidification. Some pitchstones and obsidians, however, contain as much as 10 per cent of water, while crystalline rocks rarely have more than 1 or 2 per cent. The range of mineral composition is much less in the glasses than in the crystalline aggregates, and some whole classes of crystalline rocks, such as the ultrabasic group, have no glassy representatives.

From these facts it may be inferred that many new rocks are generated in the course of consolidation of the igneous magmas and that the result will differ in accordance with the rate of crystallization, as well as according to the original composition of the magma. When the constituents of the magma are present in such proportions as to produce the lowest melting point, the mixture is said to be eutectic, and in a eutectic magma the various component minerals crystallize simultaneously, leaving the residual liquid of constant composition. In a non-eutectic magma crys-

tallization does not take place in the inverse order of fusibility, as might be expected, but in that of solubility in proportion to the amount present, as the point of saturation is successively reached. As various minerals are crystallized out, the remaining liquid is changed in composition and may attack and more or less completely dissolve some of the crystals. In many porphyries the large phenocrysts of feldspar show the corroding effects of this *resorbing* action, and thus the series may be repeated on a smaller scale. Usually the order of crystallization in a cooling magma tends to be as follows: First to form are apatite and the metallic oxides (magnetite, ilmenite, titanite, zircon) and sulphides (pyrite). Then follow the ferro-magnesian silicates, olivine, the pyroxenes and hornblende; after these the feldspars and feldspathoids (leucite and nepheline); and, finally, if excess of silica remains, quartz is formed. Minerals of the second generation are much smaller than the phenocrysts and belong to the ground-mass. Generally, however, two or more of the major minerals are thought, in considerable part, to have crystallized simultaneously.

As a final stage in crystallization is formed pegmatite, which is commonly granitic in composition, but may be a derivative of other plutonic rocks. It forms veins and dykes, cutting through the plutonic body and the neighboring country rock or as a more or less continuous fringe or selvage around its margins. The crystals in pegmatite are very large, sometimes gigantic, as in the beryl crystals of the Maine pegmatites, which have been found as much as 12 feet in length and many tons in weight, or the even more enormous crystals of spodumene ($LiAl(SiO_3)_2$) in the pegmatites of the Black Hills, South Dakota, which attain a length of 30 feet. The "mother liquor" consists of water and the other volatile constituents of the magma which have been ejected by the act of crystallization, and is at a comparatively low temperature.

"The magma or solution from which the pegmatites crystallized was igneous, in that it was the residual part of a granitic or syenitic or other igneous magma, of which the greater part had already crystallized under plutonic conditions. It was aqueous, inasmuch as it contained, perhaps very richly, magmatic water, concentrated (with other constituents) in the residual magma by continued crystallization of anhydrous minerals." (Harker.)

Differentiation. The most fundamental problem in the study of igneous rocks is to explain the great variety and diversity of

such rocks as are actually found. The explanations offered by various petrologists agree, for the most part, in one most important respect. "In general, they aim at providing some physical explanation of the derivation of diverse rocks from one parent magma." (Harker.) "There are two orders of facts to be explained: firstly, the differences between rocks constituting distinct intrusions (or extrusions), but giving evidence of derivation, more or less direct or remote from a common source; and, secondly, variation between different parts of a single rock-body, presumed to have been intruded as a homogenous magma."

"The concept of differentiation is thus an hypothesis proposed to explain various rock associations. The only rival hypothesis ever proposed was the doctrine of the mixing of two fundamental magmas (basaltic and rhyolitic), but this has been found to fail so completely that the concept of differentiation has come to be regarded as a fact as well established as the observed rock associations themselves." (Bowen.)

"When large areas of eruptive rocks are carefully investigated, it is found that there is a perfect and gradual transition of one kind into another — all intermediate varieties existing." (Iddings.)

While there is thus a general agreement among petrologists as to the derivation of all varieties of igneous rocks from a single parent magma by differentiation, there is less complete unanimity as to the manner in which the differentiation has been brought about. The preponderance of opinion, however, is that the effect is produced mainly by *fractional crystallization,* the means by which the chemist separates the different substances in a complex solution. Other agencies, such as diastrophic movements, may contribute to the same result. At one stage of crystallization, for example, the crystals may form a continuous network, in the interstices of which the residual magma is contained, much like water in a sponge. Diastrophic compression may then squeeze out this fluid and drain it away. Crystallization itself expels most or all of the water and other volatile constituents of the magma, and these expelled vapors and gases are now believed to play a very important part in volcanic eruptions.

Assimilation is the name given to the melting or remelting of solid rocks and to other processes by which they are incorporated in the magma. Much difference of opinion prevails among petrol-

ogists as to the reality and importance of this process in the genesis of rock varieties. That assimilation does occur seems to be certain, and the remelting of solidified lava by hot gases has been observed on Vesuvius (Perret), but most petrologists, at present, are of the opinion that assimilation is comparatively unimportant. After a careful analysis of the subject, Bowen writes: "Magmas may incorporate considerable quantities of foreign inclusions . . . and such action may have been important in connection with the production of certain individual masses."

Petrographic Provinces. It has long been a matter of observation that the rocks of a given region, which have been intruded, or extruded, at a given geological period, tend to have certain similarities in mineral or chemical composition, however great their diversities. These similarities distinguish them from the rocks of other regions, each of which is, in turn, characterized by its own similarities. Such a region is called a petrographic province, but time is equally important, for, at subsequent geological periods, entirely different boundaries may demarcate the region, and the same volcanic vent may send forth entirely different lavas at successive periods. In the Palæozoic Era, New England and eastern Canada formed one province; but in the Mesozoic, New England was part of a province that extended southwestward into North Carolina.

Classification. Inasmuch as the igneous rocks pass into one another by imperceptible gradations and the same magma may give rise by differentiation to many varieties, classification, though necessary, is somewhat arbitrary. "To provide a satisfactory classification of the igneous rocks . . . is one of the most difficult problems the petrologist has to deal with. The various rock-types are so intimately related, and there are so many factors to be taken into account, that any rigid and systematic arrangement is at present impossible." Despite the difficulty, there is general agreement and the classification is made according to several different criteria, none of which is entirely satisfactory. Chemical and mineralogical composition are commonly used in making the major divisions, which are subdivided according to texture and structure. The names given to the groups, such as "series," "families," etc., are differently used by different writers, but the underlying conception or genetic derivation of one from another is common to most of the schemes of classification. From

the chemical standpoint, the igneous rocks are arranged in four divisions in accordance with the proportion of silica, more or less of which is present in all igneous rocks whatever.

1. *Acid*, with more than 66 per cent SiO_2.
2. *Intermediate*, SiO_2 = 66–52 per cent.
3. *Basic*, SiO_2 = 52–40 per cent.
4. *Ultrabasic*, SiO_2 less than 40 per cent.

Another chemical division is into

1. *Alkaline Series*, in which the dominant feldspars are of the potash and soda kinds.
2. *Calc-Alkaline* or *Subalkaline Series*, in which the dominant feldspars are the lime-soda varieties.
3. *Monzonite Series*, intermediate in composition, with both alkaline and calc-alkaline feldspars.

Each of the three series includes a number of families of rocks which are defined and limited by the nature of their essential minerals. The families, in turn, are subdivided according to the circumstances of their consolidation, as registered by texture.

A very considerable number of minerals is found in the igneous rocks, but comparatively few of them in large quantity; the latter are the *essential minerals*, which characterize a given kind of rock. The others, or *accessory minerals*, may be present or absent without materially affecting the nature of the rock. With few exceptions, the igneous rocks are made up of the feldspars, or feldspathoids, together with one or more of the micas, pyroxenes, amphiboles, olivine, or quartz. The ultrabasic rocks are typically without feldspars. In addition there are small quantities of many accessory minerals among which magnetite is very common.

The *Acid Rocks* are so called because of their high proportion of silicic acid, or silica (SiO_2), but other chemical features are associated with this large siliceous content. These rocks have but small quantities of lime, magnesia, and iron; hence, they are usually of low specific gravity and light in color and, while having a relatively low melting temperature, are extremely viscous when melted.

The *Basic Rocks* are named because of the predominance of bases; they have a relatively low percentage of silica and are rich in lime, magnesia, and iron; and hence they are heavy, dark-

colored rocks which, when melted, become extremely fluid, though the melting temperature is higher than that of the acid rocks.

The *Intermediate Rocks* are, in all respects, transitional between the acidic and basic groups, and particularly so in chemical and mineralogical composition.

The *Ultrabasic Rocks* have a low percentage of silica and little or no feldspar, being made up of ferro-magnesian minerals. They are very infusible.

The division of the igneous rocks into families is made in accordance with mineralogical composition and the subdivisions of each family are determined by the texture. Six families (sometimes only five) of the igneous rocks are generally recognized, though some schemes of classification do not make use of the term *family* at all.

A. Acid Rocks

I. Granite Family

The magma, which, on solidification, gives rise to the rocks of this family, is very rich in silica (65 to 80 per cent) and has from 10 to 15 per cent of alumina; the proportion of alkalies, potassium and sodium, is relatively large (6 to 8 per cent), and there are small quantities of the oxides of iron (2 to 4 per cent), magnesium (1 to 4 per cent), and calcium (1 to 4 per cent). The principal minerals are orthoclase, with smaller amounts of plagioclase, quartz, and some ferromagnesian mineral, either hornblende or mica; the mica is more commonly black biotite; white mica, muscovite, may also be present, but seldom alone. Many accessory minerals are found in granite, but in quantities so small as not to affect the character of the rock. Differences of texture, due to the circumstances of solidification, give rise to rocks of totally different appearance, which, it is difficult to believe, are of similar or identical composition.

1. *Obsidian* is a volcanic glass, which is usually black, dark brown, or dark green, but occasionally red, yellow, or blue. It breaks with a conchoidal or clamshell-like fracture, and is translucent in thin pieces. Under the microscope, "crystallites," the incipient stages of crystallization, are visible in great numbers. The name *obsidian* is used for the varieties of volcanic glass in which the quantity of water is small; it may be 1 per cent or less, and, for precise identification, a prefix is needed, as *rhyolite obsidian,*

andesite obsidian, etc. When used without a prefix, rhyolite obsidian is meant, for, though variable in composition, the great majority of the volcanic glasses are referable to the granite family.

2. In *Perlite*, the glass is divided by concentric cracks, like the coats of an onion, due to shrinkage on cooling.

3. *Pitchstone* is much the same as obsidian, but contains more water, 5 to 10 per cent, and, perhaps in consequence of that, is less lustrous and glassy, more resinous in appearance.

4. *Pumice* is a glass which is made into an extremely light, frothy substance by the bubbles of steam and other vapors and gases; the glass was then so pasty and viscous that the bubble holes did not collapse and the result is that, when cold, the pumice is lighter than cork. When a jet of steam is blown through the molten slag from a blast furnace, material very like pumice is produced.

It happens, not infrequently, that in the course of long periods of time the volcanic rocks become *devitrified*, losing whatever glassy texture they may have had and taking on a stony one. The homogeneous mass is converted into an aggregate of extremely minute crystals of quartz and feldspar. After devitrification, the original glassy texture is indicated only by the lines of flow, or by a perlitic structure, which are not affected by the change. The same phenomenon has been observed in artificial glass, especially when the glass, owing to insufficient annealing, has been subject to internal stress, or has long been exposed to the weather, as in the windows of mediæval churches. It seems very surprising that crystallization may take place in a solid, but it must be remembered that, from the point of view of physical chemistry, glass is not a true solid, but an extremely viscous supercooled liquid.

5. *Rhyolite* ordinarily occurs as the lava outflow of a granitic magma which has been solidified quickly, yet not so rapidly as an obsidian. The texture is porphyritic and the phenocrysts are chiefly quartz and sanidine, which is the glassy form of orthoclase. The ferro-magnesian minerals are present in very much smaller quantities and, of these, the commonest is biotite. The phenocrysts are embedded in a ground mass of minute feldspar crystals and a varying proportion of glass. Other names for rhyolite are *liparite* (from the Lipari Islands) and *quartz trachyte.* Allied to the rhyolites are the *Felsites*, which are very dense, fine-

grained and light-colored rocks, from which phenocrysts are absent, or scanty, giving a compact texture. The felsites have been formed in several different ways, by the devitrification of obsidian and rhyolite, by the recrystallization of rhyolite tuffs and by original cooling from fusion.

6. *Quartz Porphyry* shades imperceptibly into rhyolite, or felsite, on the one hand, and into granite, on the other; it is made up of a ground mass of crystals of orthoclase and quartz, in which phenocrysts of quartz or quartz and orthoclase are embedded. If the phenocrysts are very abundant or the ground mass rather coarse grained, the rock is said to be a *granite porphyry* or *porphyritic granite*.

7. *Granite*. The granites are thoroughly crystalline rocks, of typically granitoid texture, to which they have given the name; the texture varies from fine to very coarse and the mineral grains are thoroughly mixed and evenly distributed, but they do not display their proper crystalline form. This is due to the manner in which the minerals interfere with one another in the process of crystallization. The characteristic minerals are orthoclase, some acid plagioclase, quartz, muscovite, biotite, and hornblende; magnetite and apatite are always present, but in small quantities. The variations in granite affect chiefly the ferro-magnesian minerals. Thus, we find *muscovite granite*, with white mica, exclusively or principally; *granitite*, with biotite only; *hornblende granite*, with hornblende replacing the mica, or in addition to biotite; and occasionally *augite granite*, with augite and biotite.

When none of the ferro-magnesian minerals is present, the rock is called a *binary granite*, or *Aplite;* if the percentage of sodium compounds is relatively high, *soda granites* result.

The color of a granite is dark or light, in accordance with the proportion of dark silicates present, and ranges from a green, so dark as to be nearly black, to almost white. The tints of the feldspars determine whether the granite shall be red, pink, or white; often the orthoclase is red and the plagioclase a very pale green to white.

8. *Pegmatite* (or *giant granite*). These very peculiar rocks occur as dykes and veins cutting through the plutonic body from which they were derived, or as marginal segments of those bodies, or as intrusions in the inclosing country rock. In composition, they are largely made up of the minerals which constitute the parent

rock, but many of the crystals are of great size and very perfect in form. Feldspar and quartz crystals from a foot to several feet in length, apatite crystals a yard long, and mica plates several feet in diameter, are not rare. In addition, pegmatites contain a great number of accessory minerals which are present either in minute quantity or not at all in the parent body. Some of these are compounds of the usual oxides, or metals, such as alumina, lime, magnesia, iron, soda, etc., with the volatile constituents of the magma which are the mineralizing vapors. Tourmaline requires boric acid, fluorite and topaz contain fluorine, and many of the minerals (*e.g.*, muscovite) form in the presence of water. Others of these accessory minerals are compounds of the rare metals; lithium, beryllium, molybdenum, etc., and sometimes the crystals attain gigantic size. The beautiful pink lithia mica, *lepidolite*, is frequent in pegmatites. As previously mentioned (p. 51), gigantic crystals of spodumene have been found in pegmatites of the Black Hills, S. D., and of beryl in those of Maine and New Hampshire. The latter are a valuable source of the metal *beryllium*, which has lately become important as an alloy of steel. In the Maine pegmatites, pockets containing gem minerals have repeatedly been found.

II. Syenite Family

In this family the magma is much the same as that of the granites, except for a smaller percentage of silica (50 to 65 per cent); the silica is almost or entirely taken up in the formation of silicates and little or none remains to form quartz, making orthoclase the chief mineral. The division into two families is not sharp, many transitional rocks connecting them.

1. *Syenite Obsidian* cannot be distinguished from that of the granite group, except by chemical analysis, but it is very much less common.

2. *Trachyte* is a lava, more or less porphyritic, consisting of phenocrysts of sanidine, with ground mass of minute feldspar crystals, and little or no glass. More or less biotite, amphibole, or pyroxene is present, in accordance with which are distinguished the varieties *mica*, *amphibole*, or *pyroxene trachyte*. In North America the trachytes are very much less abundant than the rhyolites.

3. *Phonolite* differs from trachyte in its higher percentage of soda and in the presence of the feldspathoids nepheline or leucite,

or both. The name is derived from the ringing, metallic sound which thin plates of the rock give out when struck with a hammer. Phonolites are rare rocks and in this country the Black Hills region of South Dakota is the best known locality for them. The famous Mato Tepee, or Bear Lodge (Fig. 18), is an example.

4. *Syenite* is a thoroughly crystalline rock, which is very like granite in appearance, but has very little or no quartz. The name is derived from Syene in Egypt, where so much of the ancient granite was quarried and was originally given to the rock now called hornblendic granite. Typically, syenite is composed of orthoclase and hornblende, with plagioclase, apatite, and magnetite as accessories.

5. *Mica syenite* has biotite instead of hornblende and in *augite syenite* hornblende is replaced by augite.

6. *Nepheline syenite* is characterized by the presence of nepheline and bears the same relation to phonolite as ordinary syenite does to trachyte, being the granitoid crystallization of the same magma.

B. Intermediate Rocks

III. Monzonite Family

A considerable number of rocks are included in the monzonite series and family, but many are so rare that no mention need be made here of more than two or three. The importance of the group lies in its completely transitional character between the orthoclase and the plagioclase rocks, or, in other words, between the alkaline and calc-alkaline series.

1. *Monzonite* is named from the locality Monzoni in the Tyrol. "The really characteristic feature of these rocks is that, as a rule, they carry orthoclase and plagioclase in about equal proportions." (Brögger, cited by Hatch.) "The suggestion made by Lindgren is adopted here, namely, that rocks having alkali feldspar to the extent of more than two thirds of the total feldspar are classed with the syenites, and those with less than one third with the diorites. Consequently, the monzonites embrace all those intermediate plutonic rocks in which the ratio of alkali-feldspar to soda-lime feldspar is less than two thirds and more than one third." The monzonites occur in two series, with and without quartz.

2. *Grano-diorite,* which is made the type of a distinct family by Hatch, is by Pirsson and Knopf included in the quartz-monzonites. The plagioclase feldspar predominates, as in diorite, but the percentage of silica is very high, as much as 74 per cent.

3. *Latite* is the lava or extrusive form of the plutonic monzonite.

IV. Diorite Family

The rocks of this family have about the same silica percentage as the syenites (50 to 65 per cent), but the quantity of the alkalies is less, while that of lime and magnesia is greater. Hence, the principal mineral is a lime-soda feldspar, and orthoclase is much less important than in the preceding families, or entirely absent.

1. *Andesite Obsidian* is rare and can be determined only by chemical analysis.

2. *Andesite* is a dark-colored lava of porphyritic or compact texture, composed of crystals of some glassy plagioclase feldspar and a ferro-magnesian mineral, embedded in a ground of feldspar needles or glass. According to the predominant dark mineral, we have *hornblende andesite, biotite andesite,* and several varieties of *pyroxene andesite.* These rocks, named from the Andes, are very common in the western United States and on the Pacific coast of both North and South America.

3. *Dacite* differs from andesite in having some quartz.

4. The *Diorites* are the plutonic equivalents of dacite and andesite, having a completely and coarsely granitoid texture. The ferro-magnesian mineral is usually green hornblende, but augite and other pyroxenes and biotite occur in the different varieties. Most diorites have a little quartz, and when this mineral becomes abundant, it gives a *quartz diorite,* which is related to dacite as typical diorite is to andesite.

5. *Anorthosite* is placed here because it comes under the heading "dominant feldspar plagioclase," but it is composed of a single mineral and that is a lime-soda feldspar, either labradorite or andesine. Immense areas of this rock occur in Canada, along the Saguenay, where 6,000 square miles of it are exposed and in the Adirondack Mountains of New York, with 1,200 square miles.

C. Basic Rocks

V. *Gabbro Family*

In the magmas of this series the percentage of silica is much less than in the preceding groups (55 to 40 per cent) and the quantity of the alkalies is small, while that of iron, magnesia, and lime is much greater. The principal minerals are a plagioclase feldspar rich in lime (labradorite or anorthite), some kind of pyroxene, magnetite, and frequently olivine; there is a wide range of mineral composition. Though having a higher melting point than the granites, the basaltic magma is far less viscous and may be as fluid as honey.

1. *Tachylyte* is basaltic glass, black and opaque because of finely disseminated particles of magnetite, and occurs as a selvage on basalt or in dykes. Hydration converts it into a yellowish or greenish mass called *Palagonite*. Surface flows of tachylyte are much rarer than rhyolite obsidian, but they are found among the lavas of the Hawaiian Islands.

2. *Basalt* is a name of wide application which covers many varieties. The basalts are very common volcanic rocks and basaltic lavas are extruded from most of the volcanoes now active; they are yielded by deep-sea volcanoes and oceanic islands, where granites are unknown. Usually the basalts are porphyritic, but may consist of a finely crystalline mass without phenocrysts. When porphyritic, the ground mass is made up of minute crystals mingled with a dark glass.

The basalts are closely related to the andesites and connected with them by transitional forms, but in the porphyritic andesites the phenocrysts are principally feldspars, but not in the basalts. Those varieties which contain olivine in notable quantities are called *olivine basalts*, while those in which the feldspars are replaced by nepheline or leucite are called *nepheline* and *leucite basalt* respectively. Columnar, hexagonal jointing, though not confined to the basalts, is most frequent and characteristic of them.

3. *Trap* is a useful and non-committal field name for various kinds of dark, heavy, granular rocks, which cannot readily be identified by inspection. The name is used for diorite and especially for diabase.

4. *Dolerite* is a finely crystalline, hypabyssal rock, which may be either porphyritic or granitoid in texture.

5. *Diabase* is named for its texture; the feldspar crystals are long, narrow, and lath-shaped, with the ferromagnesian mineral in the interstices. This rock is abundantly associated with the Newark or upper Triassic formation, which extends from Nova Scotia to North Carolina and, by differential erosion, the sills and stocks stand out as prominent topographical features, especially in the valley of the Connecticut River and in northern New Jersey. The Palisades of the Hudson, on the New Jersey shore, opposite the upper part of New York, and much beyond, are the edge of a thick sill and were so named because of their vertical joint columns, which, though less regular than those of the fine-grained basalts, are yet very distinct. Elsewhere, the Palisades sill is, for the most part, very irregularly jointed, though sometimes in quite regular slabs and sheets.

6. *Gabbro* is a comprehensive term for the coarse-grained, plutonic phases of the various basaltic rocks, which are typically made up of some of the plagioclases and pyroxene. *Olivine gabbro* and *hornblende gabbro* are names that require no definition. *Norite*, or *hypersthene gabbro*, contains orthorhombic pyroxene.

D. Ultrabasic Rocks

VI. Peridotite Family

The name Peridotite is taken from *peridot*, which is the French word for olivine. These rocks have a small percentage of silica (SiO_2 = 35 to 45 per cent), little or no alumina, and a very high proportion of magnesia (MgO = 35 to 48 per cent). They are without feldspar, are made up entirely of ferro-magnesian minerals and are very heavy and extremely infusible, hence they have no representatives among volcanic rocks, unless limburgite be so considered. The following table (from Pirsson and Knopf) gives the names and composition in convenient form.

Pyroxene and Olivine	Peridotite
Hornblende and Olivine	Cortlandite
Olivine alone	Dunite
Pyroxene alone	Pyroxenite
Hornblende alone	Hornblendite

The ultrabasic rocks sometimes occur separately and independently, as dykes, sheets, laccoliths, or small stocks, but they also are found together; more commonly, they occur in connec-

tion with bodies of gabbro, sometimes as phases, sometimes cutting the gabbro in dykes. No fragmental rocks, such as ashes, or scoriæ, of this composition are known to occur.

1. *Limburgite* is an ultrabasic lava and is usually assigned to the peridotite family; it contains augite and olivine embedded in a glassy base; magnetite is always present.

Some petrologists divide the ultrabasic rocks into two or more families, depending upon the presence or absence of olivine.

2. *Serpentine*, a name which is used for both mineral and rock, is derived from the alteration of olivine and augite, and probably the greater part of the serpentine which is found in various lands is derived from the alteration of peridotite and pyroxenite. Some of this alteration may be due to the ordinary processes of weathering; on a great scale, the change is rather to be attributed to the magmatic vapors and solutions which accompany the intrusions themselves.

MEGASCOPIC CLASSIFICATION OF IGNEOUS ROCKS

		(a) Feldspathic Rocks, generally light-coloured. (ferromagnesian minerals are minor in quantity						(b). Ferromagnesian Rocks, generally dark coloured	
		Orthoclase (Predominant feldspar)		Orthoclase and Plagioclase		Plagioclase (Predominant feldspar)		rith Plagiocla	without Plagioclase
		with Quartz	without Quartz	with Quartz	without Quartz	with Quartz			
I. Phanerites (grained rocks; composed wholly or largely of recognizable constituents) Intrusive	Non-Porphyritic	Granite (1) Aplite	Syenite Nephelite Syenite		Monzonite	Quartz Diorite	Diorite *Anorthosite	Gabbro	*Peridotite *Peroxenite *Hornblendite ·Dunite
	Porphyritic	Granite Porphyry	Syenite rphyry	Quartz Monzonite * Granodiorite Porphyry	Monzonite Porphyry	Quartz Diorite Porphyry	Diorite Porphyry	Gabbro Porphyry	
II. Aphanites (All constituents except plenocrysts unrecognizable)	Porphyritic	Rhyolite Quartz porphyry	Trachyte	Latite		Dacite	Andesit	Basalt	
			Felsite	Porphyry			Porphyry	Porphyry	
Extrusive or intrusive near Earth's surface	Non-Porphyritic	Felsite					Andesite	Basalt	
III Glasses (composed wholly or largely of glass)	Non-Porphyritic	Obsidian†, Pitchstone, Perlite, Pumice						Tachylyte	
	Porphyritic	Vitrophyre (Obsidian porphyry and Pitchstone porphyry)							
IV. Fragmental Igneous material Beds. strata		Tuffs, Breccias (Volcanic ash, etc)							

(1). A fine grained granite with little or no ferromagnesium mineral occuring as dikes.
(2). A coarse grained facies of the granite occuring as dikes or segregations
* No volcanic equivalent.
† Most Obsidians are dark coloured.

(This table of the igneous rocks is modified from that of Pirsson and Knopf by A. F. Buddington.)

THE PYROCLASTIC ROCKS

These rocks are, in a sense, hybrids between the igneous and the sedimentary classes; the material is of volcanic origin, the deposition and arrangement sedimentary. The finer material, so-called volcanic ash and dust, may be mixed, in any proportions, with ordinary sediments, sand, clay, mud, etc., and being deposited by wind or water, is stratified. Very large fragments, such as blocks and bombs, are too heavy for the sorting action of the wind and are not stratified; these accumulate at no great distance from the vent.

1. *Volcanic Agglomerate* is a mass of angular blocks of lava, with which may be mingled, to a greater or less degree, fragments of sedimentary rock torn off from the sides of its chimney by the uprushing gas column. The blocks may be loose or consolidated into a rock by finer material which fills the interstices. The Absaroka Mountains on the eastern side of the Yellowstone Park are chiefly made up of an immense mass of volcanic agglomerate, cemented by ash into a rather soft rock, which weathers rapidly. The exposure of the blocks produces the most fantastic topography imaginable.

2. *Volcanic Ash* (a misnomer, as hereafter explained) is made up of minute fragments of glass, which have a characteristic shape from their having formed part of the bubble-walls. Mixed with these are excessively small, but determinable fragments of phenocrysts, the whole comminuted by the volcanic explosions and transported great distances by the wind. The finest dust, such as was disseminated from Krakatau in 1883, may be distributed, in infinitesimal quantities, all over the world. The somewhat coarser-grained ash is transported hundreds of miles and, when at last dropped, may form thick beds of the pure ash, or may be deposited in water and mixed with sediment in any proportions. In western Kansas and Nebraska are beds of pure ash 25 feet, or more, in thickness, which must have been carried 400 miles, at least, from the vents. In the White River bad lands of South Dakota, the clays, which are the predominant material, have considerable quantities of ash disseminated through them, and, near the top of the formation, are thick beds of pure white ash which, at a distance, look like snow banks.

3. *Tuff* is volcanic ash or lapilli cemented into a more or less compact, generally soft rock by the action of water. The tuffs

are usually sorted and stratified and often contain an abundance of fossils. When deposited in water, tuffs contain more or less ordinary sediment, and, by increase of this element, a tuff may pass gradually into a shale, or mudstone, or sandstone. The tuffs and volcanic agglomerates and breccias may best be classified in accordance with the nature of the component material. With the exception of the ultrabasic rocks, all of the igneous families are represented and the names are taken from the lava phase.

4. *Bentonite* is a decomposition product, yet should be mentioned here because of its significant implication, giving proof of volcanic accumulations where, at present, no other evidence of their existence can be found. Bentonite is derived from volcanic ash and is very thoroughly decomposed, but retains characteristic features of ash and tuffs. It is defined by C. S. Ross and E. V. Shannon as follows: "Bentonite is a rock composed essentially of a crystalline, clay-like mineral formed by the devitrification and the accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash, and it often contains variable proportions of accessory crystal grains that were originally phenocrysts in the volcanic glass. . . . The characteristic clay-like mineral has a micaceous habit and a facile cleavage, high birefringence and a texture inherited from volcanic tuff or ash."

Bentonites have been identified in Palæozoic rocks from Nova Scotia and New Brunswick, through Pennsylvania and Virginia to Alabama, Arkansas, and Oklahoma. The most widespread occurrence of them, so far known, is in Kentucky, Tennessee, and Alabama, in the Ordovician. In Nova Scotia and New Brunswick, Arkansas and Oklahoma, they are in the lower Carboniferous and in Texas and New Mexico, they are Permian in date. Very unexpected was the discovery of bentonite in the Tertiary formations of the Gulf Coast.

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CHAPTER IV

IGNEOUS ROCK MASSES

In structure, the igneous rocks are characterized by the absence of stratification and hence they are also called *unstratified* or *massive* rocks. The forms assumed by igneous rock masses are those due to the solidification of liquid magmas within the earth's crust or upon its surface and are, therefore, characteristically different for plutonic and volcanic masses.

Plutonic Bodies

The classification of plutonic bodies of rock may be made in several different ways. The plutonic rocks are *intrusive*, having forced their way, or been forced, into older, preëxistent rocks, filling fissures and cavities which they have found, or, more generally, have made for themselves. In places accessible to observation the rock intruded is usually of the sedimentary class, but may be metamorphic or igneous. Whatever its nature, the rock which is invaded is called the *country rock* and is, of necessity, older than the intruding rock; it may be vastly older, measured by millions of years. The geological date of an intrusion may sometimes be determined by finding the newest strata which they have traversed and the oldest which would have been traversed, had they been in existence.

Professor Daly's classification is according to the form of the plutonic bodies and is an ordered description. The first division is into two primary groups, (1) subjacent and (2) injected bodies. Subjacent bodies are those which rest upon no floor of the country rock, but enlarge downward indefinitely, so far as they can be followed by observation. An injected body is one which is completely inclosed by the country rock, except for the comparatively narrow feeding channel along which the magma rose.

Both subjacent and injected bodies may be *simple*, *i.e.*, composed of material intruded at one period; *multiple*, made up of material of the same kind, intruded at more than one period; or *composite*, composed of material derived from different kinds of magma, intruded at different periods. The distinction is thus according to time and the chemical character of the rock. Even a simple intrusion may, however, be compound in the sense of being made up of several connected bodies, simultaneously formed and derived from the same magma. (Fig. 9, p. 72.)

I. Subjacent Bodies

The manner in which the plutonic bodies of this group have reached the position which they now occupy is very problematical and gives rise to much difference of opinion. How far the magma

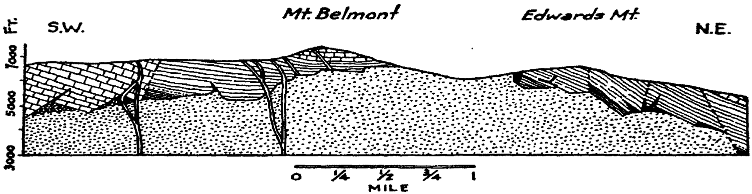

FIG. 3. — Section across the batholith of Marysville, Mont., showing roof of stratified rocks. (From Harker after Barrell)

was active and forced its own way upward through the overlying rocks and how far it was passive and *squeezed* up by movements of the earth's crust, are debatable questions. Presumably both processes have been concerned in varying combinations. From the purely descriptive point of view, the particular characteristic of these subjacent bodies is their downward increase in diameter to unknown depths and the lack of any observed floor of country rock upon which they rest.

Batholiths (or bathyliths) are enormous masses of plutonic rock, hundreds, or even thousands, of miles in diameter, which have been exposed by the removal of the overlying country rock, and their shape is determined by the amount of this removal. Some batholiths, as exposed to view, are of irregular shape, no one

diameter greatly exceeding the others. Sometimes, however, they are long, narrow belts, such as the batholiths of granite which form the cores of the Rocky Mountains and the Sierra Nevadas. Laid bare to greater depths, their shapes would change.

All other forms of igneous intrusion are, very probably, connected with batholiths and were given off from them, though such connection can rarely be seen. The same would seem to be true of volcanoes, which are merely such plutonic intrusions as happened to reach the surface.

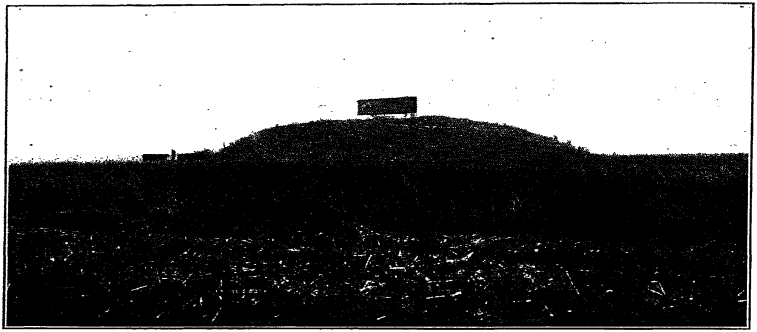

Fig. 4. — Little Snake Hill, Newark Meadows, N. J., a stock rising from the Palisades sill.

Stocks, or *Bosses*, are rounded masses of plutonic rock, which vary in diameter from a few feet to several miles. They have cut across the country rock, which, in some instances, they have pushed aside and, in others, have clearly perforated. From stocks, as from batholiths and all other forms of intrusive masses, are frequently given off tongues, or *apophyses*, which penetrate the country rocks as veins, dykes, sills, and various irregular protrusions. Granite, diorite and gabbro are especially common in stocks, and the texture of the rock frequently grows coarser from the circumference toward the center of the body. Stocks and batholiths differ chiefly in size, so that the distinction between them is somewhat arbitrary.

Stone Mountain, in Georgia, is a large stock which, no doubt, protrudes from an underlying batholith. Great and Little Snake Hills, which rise out of the Newark marshes in New Jersey, are

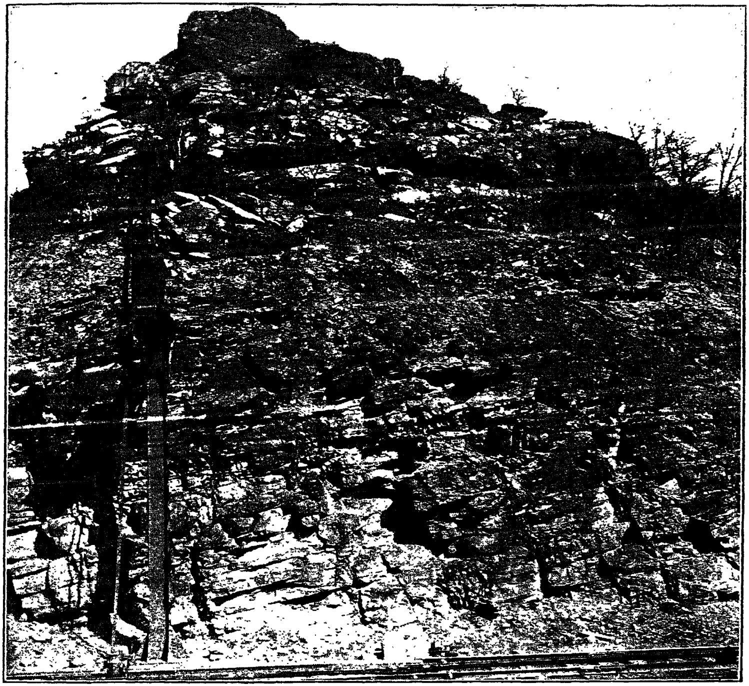

FIG. 5.—Southwest end of Great Snake Hill, Newark Meadows, N. J., a stock. Below and in foreground, Newark sandstones; intrusive body above and behind.

stocks which are given off from the great sill of the Palisades. In this case, the distinction between subjacent and injected bodies becomes somewhat vague.

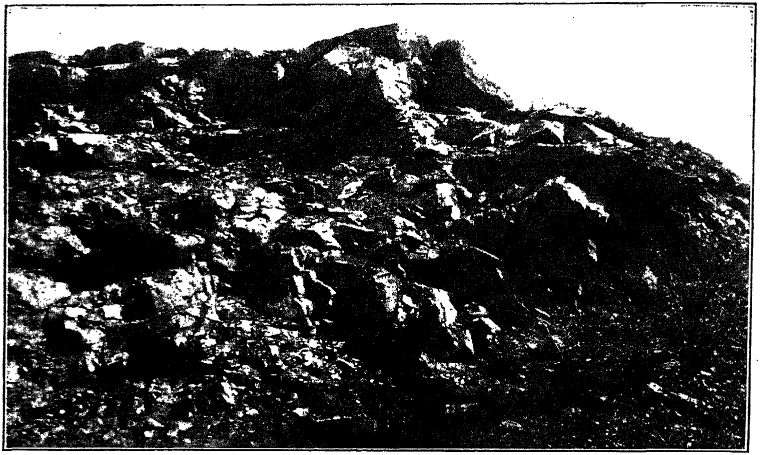

FIG. 6. — Southwest end of Great Snake Hill, N. J., view at right angles to Fig. 5 and showing only igneous rock.

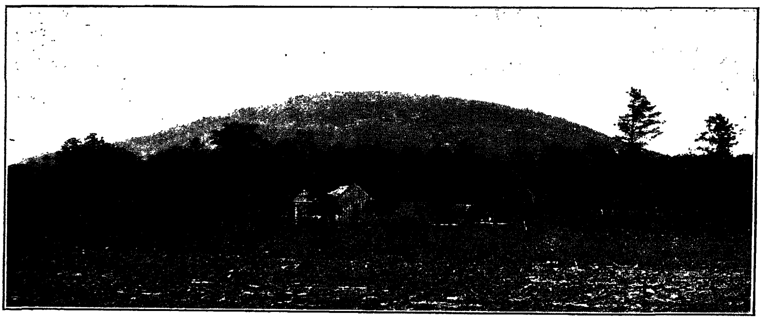

FIG. 7. — Stone Mountain, Ga. (Photograph by Gilbert, U. S. G. S.)

II. Injected Bodies

These are of a great variety of shapes and sizes and differ in their relations to the inclosing or country rock. Magmas are very different in their degree of fluidity, or viscosity, according to their mineral composition, and, consequently, the injected body represents the line of least resistance for that particular magma, in those particular circumstances.

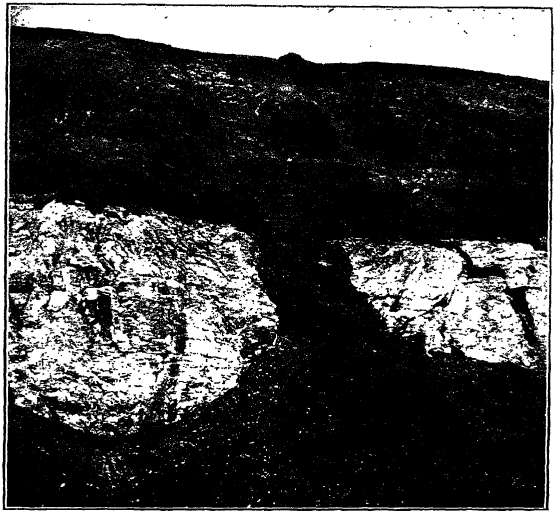

FIG. 8.—Chalk and overlying sheet of diorite cut by dyke of basalt, Cave Hill, Belfast, Ireland. (Photograph by Prof. S. H. Reynolds)

Dykes. A dyke is a vertical or steeply inclined wall of igneous rock formed by the filling of a fissure by the ascending magma, and its subsequent consolidation. Dykes of a certain kind may actually be observed in the making, as when the lava column of a volcano bursts its way through fissures in the cone. Dykes may occur in any kind of country rocks, but most of those which are exposed to observation have invaded sedimentary rocks, in

which they always cut across the planes of stratification. In thickness, they vary from less than a foot to several hundred feet, but are always very narrow in proportion to their length. Ordinarily, the length of a dyke may be a few miles, or tens of miles, and, for the most part, they follow straight courses. The Great Dyke of Rhodesia is several hundred miles long and perfectly straight, but this remarkable structure has certain peculiar features which make its real nature somewhat problematical.

Fig. 9. — Compound dykes of diabase cutting pegmatite, Mt. Apatite, Me.

The fissures, now filled by dykes, may or may not have reached the then surface of the ground; if so, lava sheets and flows were poured out; if not, only the more or less vertical dyke resulted. Dyke rocks usually are of compact texture, having cooled and solidified more slowly than the surface lava-flows, though the edges, chilled by the walls of the fissure, may be glassy.

The results of erosion and weathering upon dykes will depend upon the relative resistance of the dyke and the country rock and of the kind of agent that has been most active in the work of erosion. In the northern United States and Canada, which still show very conspicuously the effects of comparatively recent glaciation, dykes and including rocks are commonly worn down to the same level, since a glacier grinds away hard and soft rocks alike. Figure 9 shows a mass of pegmatite cut by several parallel

dykes of a basaltic rock, photographed in a quarry at Mt. Apatite, near Lewiston, Maine. Both of these very different rocks were worn down to the same level by the ice. The dykes are simple, in the sense that they are composed of material intruded at one period, complex in that they have several bodies with connections from one to another.

If the country rock is eroded away more rapidly than the dyke, the latter is left standing above the surface like a wall, and the

FIG. 10.—Basalt dyke, in relief, coast of Scotland. (Geol. Surv. Gt. Brit.)

dykes may be so numerous as to form a network of intersecting walls, as in the part of Wyoming and Montana which lies to the northeast of the Yellowstone Park. Sometimes, but less frequently, the igneous body disintegrates more rapidly than the inclosing rock and then a trench results, as occurs in the Triassic dykes of North Carolina.

Intrusive Veins are smaller, more winding, and frequently branching fissures, which have been filled with magma and may often be traced to the larger body from which they were given off. In pegmatite veins the minerals are in immense crystals, which could not have formed from simple fusion.

Sills, or Intrusive Sheets. These are horizontal or moderately inclined masses of igneous rocks which are concordant with the stratification of the sedimentary rocks between which they are

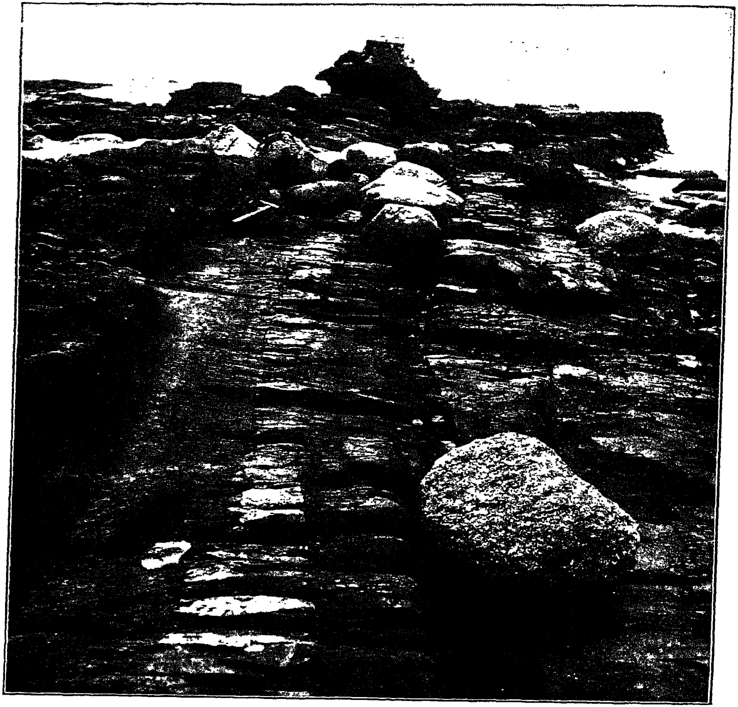

Fig. 11. — Compound dyke of dolerite cut down by the sea, Port a Buidhe, Arran, Scotland. (Geol. Surv. Gt. Brit.)

found; the thickness is small in relation to the lateral extension. A sill often runs for long distances between the same two sedimentary strata (for they do not intrude older igneous bodies), but

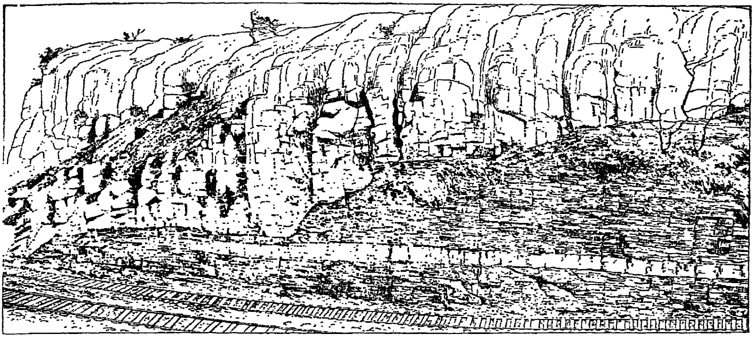

FIG. 12.—Palisades sill overlying Newark shales and sandstones; a much smaller sill, below, is concordant with the bedding. (Darton)

FIG. 13.—Sill of dolerite, cutting across beds of sandstone, near Kinghorn, Fife, Scotland. (Geol. Surv. Gt. Brit.)

if they can be traced far enough, they may generally be found to cut across the strata at one point or another, and to be connected with a dyke, which was the feeding channel along which the magma rose. A dyke may give off one or more sills laterally or the sill may, as it were, rest on the dyke.

In thickness, sills vary from a few feet to several hundred feet. The Palisades of the Hudson are the outcrop along the river bank of a great sill, 70 miles long and in thickness from 300 to 850 feet.

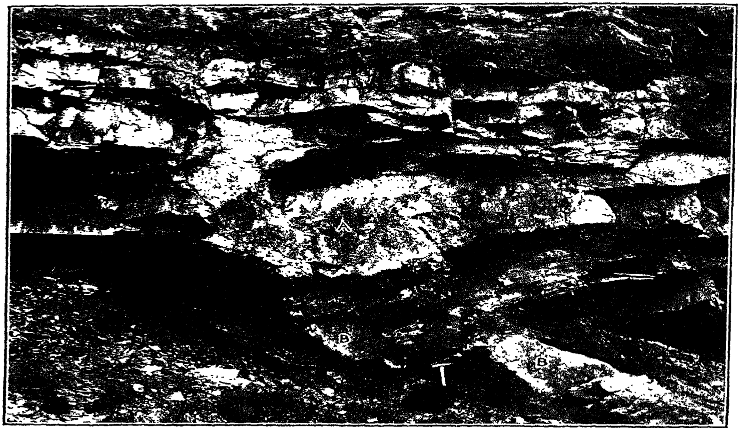

Fig. 14. — Sill of "white trap," A, connected with dyke, B, B, near Burntisland, Fife, Scotland. (Geol. Surv. Gt. Brit.)

The southern outcrop of the same sheet is Rocky Hill 50 miles or more to the southwest, and the intervening area is covered over with thick masses of sandstones and shales, but borings of various kinds prove the continuity of the sill between the two outcrops.

Sills occur usually in horizontal or moderately inclined strata and were very generally formed by magmas which are least viscous in the molten state, *i.e.*, of the gabbro family. It is probable that sills can be formed only at moderate depths below the surface, because the overlying strata must have been lifted by an amount equal to the thickness of the sill. Certain cases are known, how-

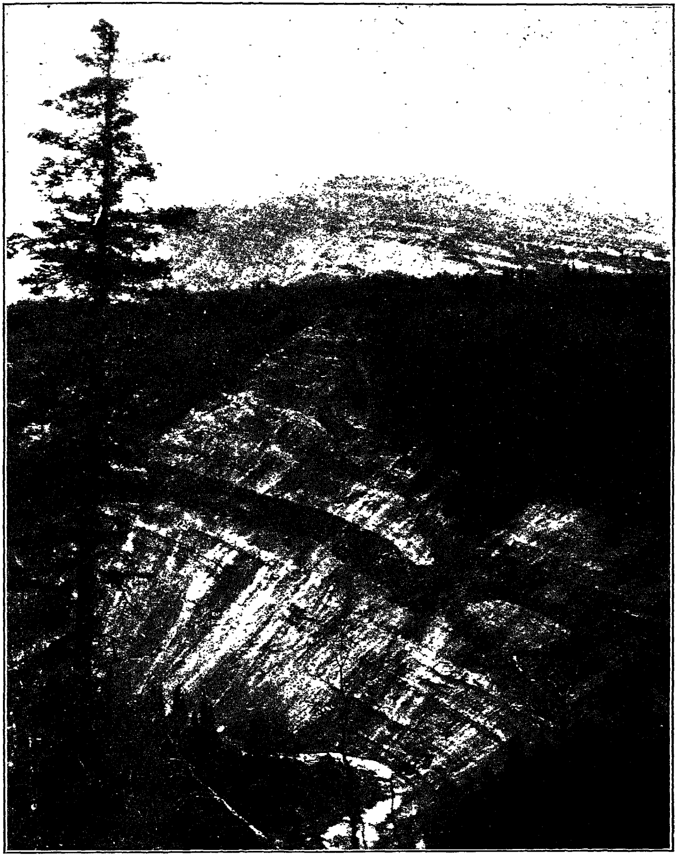

FIG. 15. — Sill and dyke in bedded rocks, Lower Boulder Creek, Alaska. (Photograph by Capps, U. S. G. S.)

ever, in which an intruding sheet appears to have made its way by melting and incorporating some of the strata, especially the limestones. At great depths, the weight to be lifted is so enormous that the path of least resistance for the ascending magma is found by breaking across the strata.

In a limited exposure, it is often difficult to distinguish between a sill and a lava sheet, which, originally poured out on the surface of the ground, has been buried by the deposition of sediment upon it and is thus an interbedded or contemporaneous volcanic sheet (see p. 94). The latter is indicated by scoriæ or other fragmental products, which cannot form under plutonic conditions, by the texture of the rock, more or less glassy, or porphyritic, and by the

FIG. 16.—Little Sun-Dance Hill, S. D., a laccolith with nearly intact cover of strata. (Photograph by Darton, U. S. G. S.)

nature of the contact with the overlying stratum. In the lava sheets, the cracks and fissures of the upper surface are filled with sediment like that which composes the overlying bed.

On the other hand, if the *overlying* stratum shows the effect of alteration by heat, or if the sill can be found cutting across the strata at any point, or if it can be traced to a dyke which extends above it, or finally, if pieces of the overlying bed have been torn off and imbedded in the magma, then the intrusive nature of the sheet will be demonstrated.

Laccoliths. A laccolith (or laccolite) is a large, lenticular mass of igneous rock, filling a chamber which it has made for itself by lifting the overlying strata into a dome-like shape; the magma was supplied from below, it is believed, through a small pipe, or fissure, but no such feeding channel has been actually observed. The igneous mass is the solidified magma of the highly viscous, siliceous kinds, which can more easily arch up the superjacent

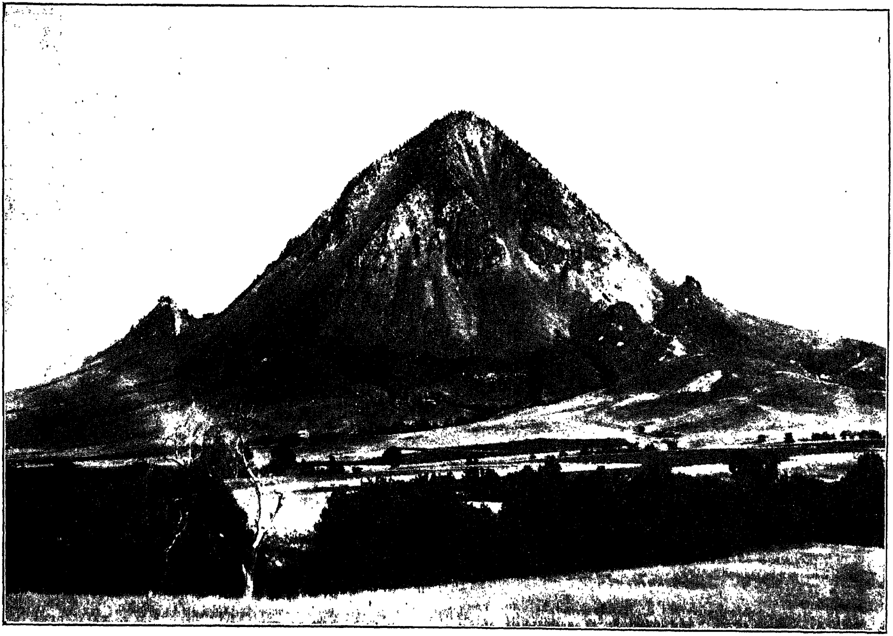

FIG. 17. — Bear Butte, S. D., a laccolith with plutonic mass exposed; upturned strata around base. (Photograph by Darton, U. S. G. S.)

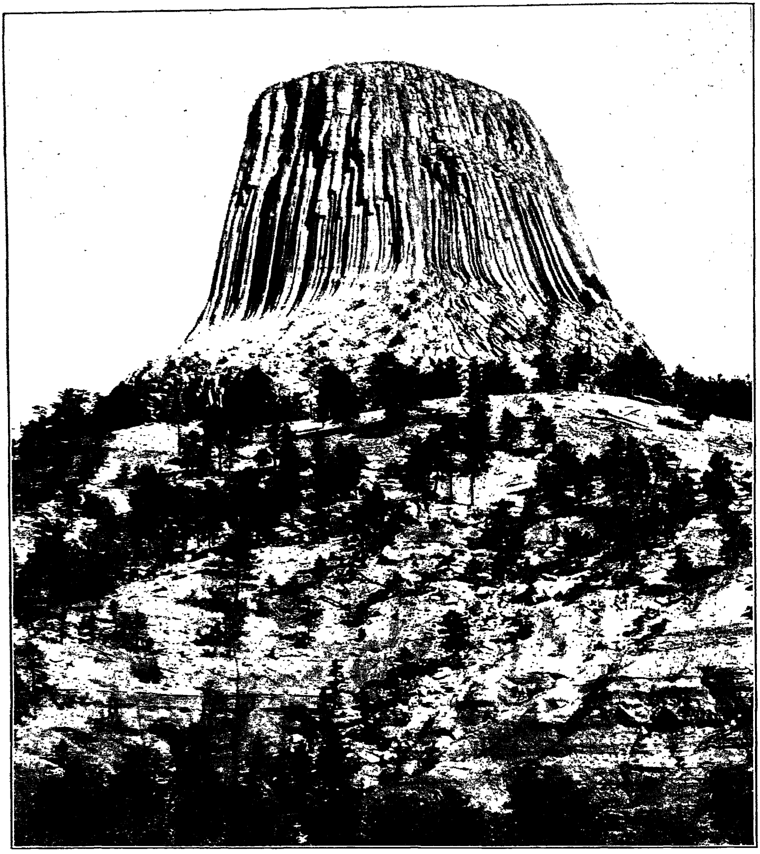

FIG. 18.—Mato Tepee, columnar phonolite resting on platform of stratified "Red Beds," S. D., believed to be the core of an eroded laccolith. (Photograph by Darton, U. S. G. S.)

strata than force its way between them. Sills, it is true, are often given off from laccoliths, but they are of quite subordinate importance, while dykes and irregular protrusions, called *apophyses*, extend into fissures of the country rock.

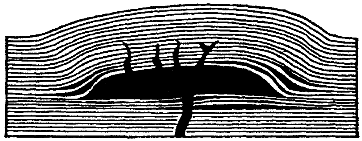

Fig. 19. — Diagram section of laccolith. (Gilbert)

Laccoliths occur in a great variety of shapes and sizes, according to the modifying circumstances of intrusion. First described and named by Mr. Gilbert in the Henry Mountains of southern Utah, where they range from ½ mile to 4 miles in diameter, of oval ground-plan, and in height from ⅓ to ⅐ of their horizontal diameter, they were subsequently found in other parts of the western United States and over the world generally. A very interesting group of laccoliths rises from the plain northeast of the Black Hills of South Dakota and displays various degrees of

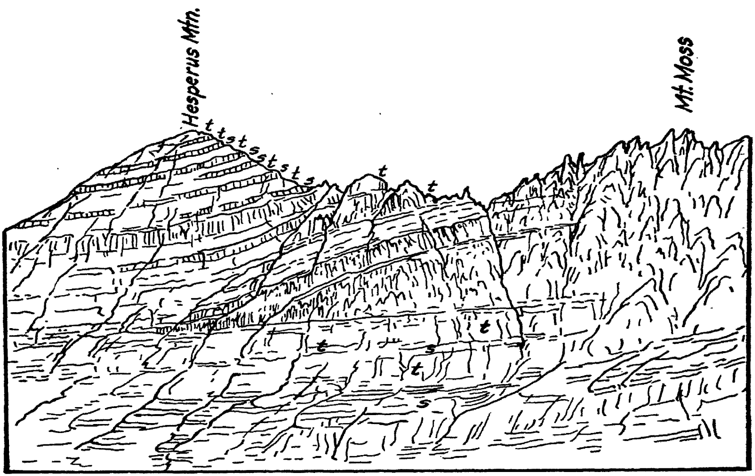

Fig. 20. — Eroded laccolith with many sills and apophyses, Rocky Mountains, Col. *s*, sandstone; *t*, trachyte. (Holmes)

erosion of the intrusive body and the cover of stratified rocks. Little Sun-Dance Hill is a small dome from which only a part of the stratified cover has been removed and the igneous core is nowhere exposed. There can, however, be little doubt of its

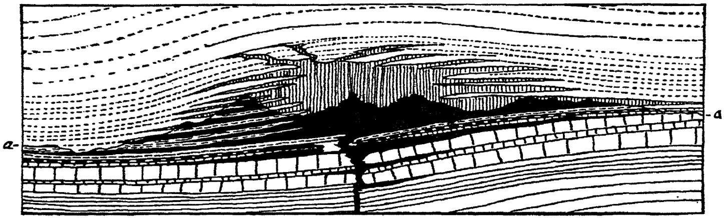

Fig. 21. — Restoration of laccolith shown in Fig. 20. *a, a*, present surface; full black, intrusive body; vertical lines, parts of intrusive body removed by denudation. (Holmes)

existence beneath the overarching strata. In the same area is Bear Butte, from which the cover of sedimentary rock has been removed, except around the base, where the strata are upturned. The igneous core, which is fully exposed, is remarkable for its great height as compared with its diameter. Mato Tepee (Bear

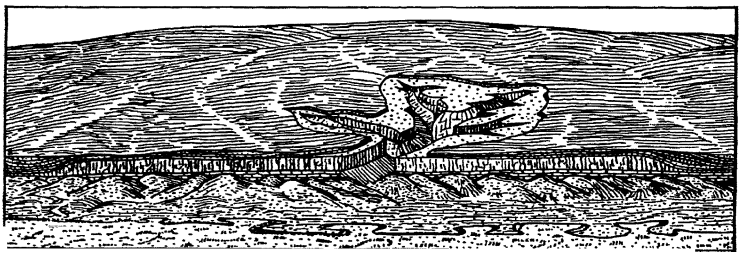

Fig. 22. — Shonkin Sag laccolith, Mont. (Pirsson)

Lodge, also called the Devil's Tower), one of the most remarkable landmarks of that whole region, is a magnificent shaft of columnar phonolite, which rises abruptly to a height of 700 feet. It stands upon a platform of undisturbed, horizontal beds of sandstone and

is believed to be the remnant of a laccolith from which the covering strata and much of the igneous core have been removed by erosion.

Shonkin Sag laccolith, in the Highwood Mountains of Montana (Figs. 22 and 23), is a transition between laccolith and sill.

FIG. 23. — Igneous body of Shonkin Sag laccolith. White band syenite segregated in shonkinite. (Pirsson)

Figure 20 shows a modified form of laccolith, found in the La Plata Mountains of Colorado, called the "cedar tree type," from the many sills given off from the central mass, which distinguish it from the ordinary "mushroom type." More or less asymmetrical modifications of the typical form are not uncommon.

FIG. 24. — Gabbro cut by granite dykes, Hastings, Ont. (Geol. Surv., Canada)

Bysmaliths are an extreme form of the laccolithic intrusion, of which the typical instance is Mt. Holmes in the Yellowstone Park. Not many have yet been found. The periphery of the intrusive body is very steep, almost vertical, with a sharp disruption of the surrounding strata, but passing into a dome-like uplift of those strata above the igneous body; downward the latter terminates

abruptly at the level of the base, below which the strata are undisturbed.

Lopoliths are, as it were, inverted laccoliths, with lower surface convex and upper surface plane. The body of gabbro at Duluth, Minnesota, and the copper-nickel-bearing igneous mass at Sudbury, Ontario, are examples.

Phacoliths are lenticular bodies of igneous rock, peculiar to folded strata, which occur along the crests and troughs of undulating beds, in which sills are not found.

FIG. 25.—Inclusions (xenoliths) of schist in granite. (U. S. G. S.)

Chonoliths are irregular intrusive bodies, injected into dislocated rocks, and their shapes are so irregular and their relations to the country rock so complex, that they cannot be referred to any of the preceding categories.

The foregoing classification of plutonic bodies, proposed by Professor Daly, is descriptive and independent of any theoretical considerations. Mr. Harker's genetic classification should also be employed as essential to an understanding of the geological relations of the plutonic bodies. Igneous action is closely associated with diastrophic movements of the earth's crust, and of these movements, as will be seen (Chap. IX), there are two kinds: the orogenic, or mountain-making, and the epeirogenic, or plateau-

making (literally, continent-making). The orogenic movements produce folding of the strata, while the epeirogenic cause a broad uplift of the surface; each kind of movement has its particular sort of igneous intrusions. "Where the crustal stresses, as shown by the displacements, have been of a more mixed character, the contrast may be obscured and intermediate forms may occur. Under each of the two categories thus recognized are comprised intrusions of widely different habits. The most obvious differences are seen in the diverse postures assumed by the intruded rock-bodies and their attitude toward the 'country' rocks in which they are intruded. It is evident that we are still dealing with the effects of different distributions of crustal stress, partly modified, however, by preëxistent structures in the country rocks." (Harker.)

In accordance with the relations of the plutonic bodies to the intruded rocks, there may be distinguished the *concordant* and the *transgressive*, terms which imply that, ordinarily, the country rock is stratified; when it is igneous, as in granite, for example, the terms are inapplicable. In concordant intrusion the magma has been directed by lines of weakness, such as bedding planes, and plutonic bodies like sills and laccoliths are the result. The transgressive bodies have broken across bedding planes and other structural lines, and such forms as dykes and stocks are the result. Concordant bodies, unless greatly disturbed after their formation, tend to be horizontal or to form low angles with the plane of the horizon, while transgressive bodies form high angles with that plane.

Harker's arrangement may be thus tabulated:

I. *Orogenic*	II. *Epeirogenic*
1. Concordant	1. Concordant
Phacolith	Sill
	Laccolith
	Bysmalith
2. Transgressive	2. Transgressive
Stock	Stock
Dyke	Dyke
Batholith	Batholith

The distinction of mountain and plateau types of intrusion, while characteristic, is not sharply drawn. Dykes, stocks, and batholiths are common to both, and laccoliths may occur in folded as well as in undisturbed strata.

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CHAPTER V

VOLCANIC ROCKS — VULCANISM

Vulcanism is but a small and relatively unimportant part of igneous activity, that part which happened to break through to the earth's surface. To the geologist, however, volcanoes offer the preëminent advantage of enabling him to observe the actual genesis of igneous rocks under surface conditions, while the mode of formation of plutonic rocks must be inferred from a study of the cold and solidified masses that are exposed to view by erosion. The original magmas are the same for both types, but the circumstances under which solidification took place are so different that the texture, structure, and appearance of volcanic rocks are radically different from those of the plutonic class. Here again, however, there is gradation from one class to the other, because of the actual continuity of material.

Volcanic rocks are of two very different kinds: the lavas, which are extruded in a molten state, and the fragmental materials, which are due to violent explosions within the volcano.

Lava is the name given to magma that has been erupted on the surface of the land or bottom of the sea, and in chemical and mineralogical composition the lavas correspond to the various plutonic rocks, though generally differing from them greatly in appearance, especially in color and texture, so that they have received different names. Thus, the lava of a granite magma is *rhyolite;* of a syenite magma is *trachyte; dacite* and *andesite* are the effusive forms of the diorite family and the various basalts of the gabbro family.

Magma contains a great quantity of vapors and gases, chief of which is steam, but HCl, HF, SO_2, CO_2 are also abundant, as well as certain substances such as sulphur, borax, ammonium chloride, which are solid at ordinary temperatures. These all act as fluxes, *lowering the melting and freezing point of the magma,* as common salt lowers the freezing point of water. When the lava

is erupted, the contained vapors and gases begin to escape and the lava to freeze and solidify.

How long the process of solidification goes on, depends upon the chemical composition of the magma, which determines viscosity. Contrary to the statement frequently made, granite is more fusible than gabbro, but the latter is far more liquid, less viscous. The very liquid lavas of the Hawaiian Islands are basaltic in composition, but they flow fifty miles or more before coming to rest through freezing, while acid lavas are so stiff that often they flow but a few feet, or not at all, from the vent.

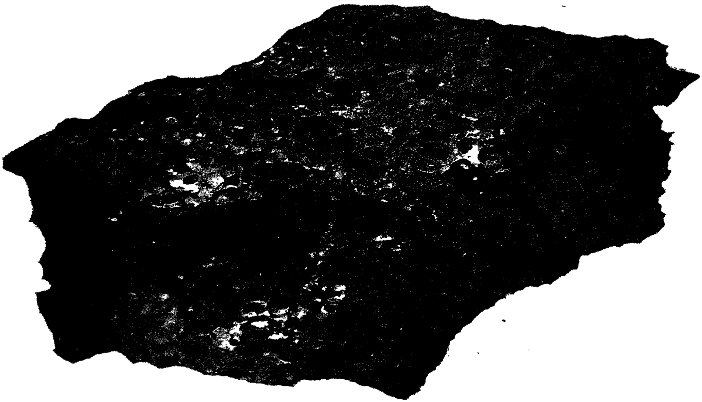

FIG. 26.—Fragment of scoria, one-half natural size, Sunset Peak, near Flagstaff, Ariz. (Photograph by J. R. Sandidge)

The surface of a lava flow is usually covered with cindery, slaggy masses, called *scoriæ*, of pumiceous, or scoriaceous structures (p. 49). These are rock froth made by the bubbles of the escaping vapors and gases, the rock stiffening and solidifying before the bubbles collapse. There is quite a complete analogy between scoriæ and leavened bread; so long as the yeast plant (*Torula*) is active, it generates carbon dioxide, the bubbles of which convert the dough into a sponge. If the loaves are put into the oven at the proper time, the dough is solidified and forms a light, spongy bread, full of bubble-holes. If allowed to stand too long before baking, the gas

escapes, the bubbles collapse, and the loaf is an uneatable, doughy mass; the bread is said to be *heavy*. Similarly, pumice and scoriæ solidify while still a frothy mass and the difference between them is one of degree. Pumice is a frothy obsidian, the threads and films between the cavities are plainly of glass, even to the unassisted eye, and the blocks are so light that they float upon water, often for many months, and are carried long distances by marine currents before becoming water-logged and sinking.

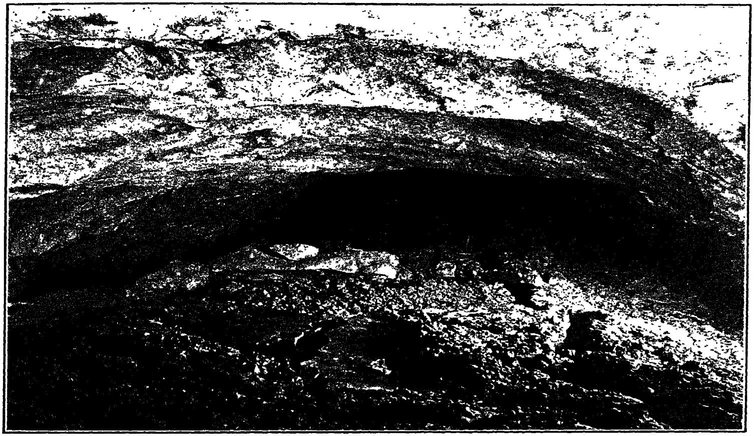

FIG. 27. — Lava tunnel showing fragments of the roof fallen into the still fluid lava below, near Flagstaff, Ariz. (Photograph by H. S. Colton)

As is the case in all liquids, whether thin or viscous, the motion of a lava-stream is not a glide, but a roll, as is equally true of a river. The bottom of the stream is retarded by friction with the surface over which it flows, while the top, advancing more rapidly, is continually rolling down at the convex front of the flow, so that the scoriaceous crust, though formed only on the surface of the flow, is rolled underneath it, inclosing the molten mass in an envelope of scoriæ. The movement of the lava-flow breaks up this thin, slaggy crust into loose slabs and blocks. The highly viscous lavas are soon covered with heaped-up cindery masses, while those that

are more liquid have curiously twisted, ropy surface crusts, very much like the slag from an iron furnace. In Hawaii, the ropy lavas are called *Pahoehoe* and the block lavas *Aa*, native names which are quite generally used by American geologists. *Pillow-lavas*, which are made up of rounded, cushion-like masses, are interpreted as being submarine flows. Scoriæ are very bad conductors of heat, and thus the scoriaceous envelope retards cooling and keeps the lava-flow hot, often for many years. Humboldt

FIG. 28.—Side of *Aa* flow from Mauna Loa, April, 1926. (Photograph by T. A. Jaggar)

observed that the lava from Jorullo, in Mexico, was still so hot fifty years after extrusion, that a stick, thrust down into a crevice, would take fire, and lava-streams near the summit of Ætna may flow over snow fields without melting them.

The arched surface of cindery blocks may become self-supporting and then the still fluid portion of the lava flows away from beneath the crust, forming long tunnels. Such tunnels are especially well shown in Iceland and the Hawaiian Islands. The distances to which lava-streams flow and the rapidity with which they move are determined by the slope of the ground and the fluidity of the lava. A lava flood from Mauna Loa, Hawaii, flowed fifteen miles in two hours, but this is unusual and owing to the great fluidity of the lava. Ordinarily, a lava-stream is not a true liquid, but is made up of larger and smaller crystals, embedded

FIG. 29. — *Aa* flow from Sunset Peak, Ariz. (Photograph by H. S. Colton)

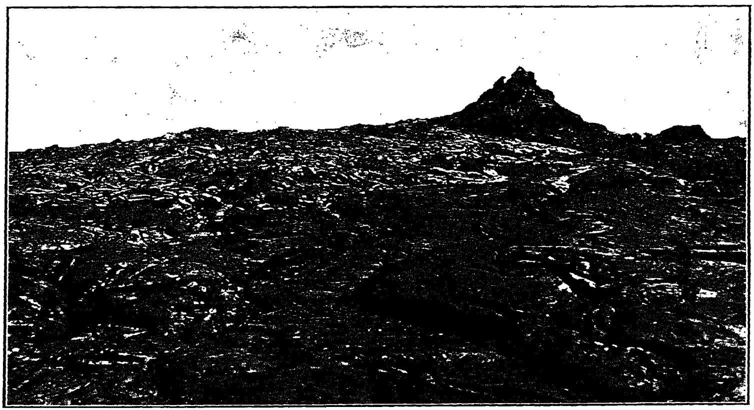

FIG. 30. — Two kinds of *Pahoehoe* and spatter cone on edge of Halemaumau, Hawaii, April 17, 1919. (Photograph by T. A. Jaggar)

in a pasty mass and the whole saturated with gases and vapors. Some lavas appear to owe their mobility almost entirely to these vapors, just as candy, made by boiling down a syrup, remains plastic and mobile so long as it is hot and the crystals of sugar are cushioned by steam. When cold and dry, the candy becomes rigid, even brittle.

Beneath the scoriaceous crust the lava congeals into a compact, stony, or glassy body. Down to a certain level, the rock may be

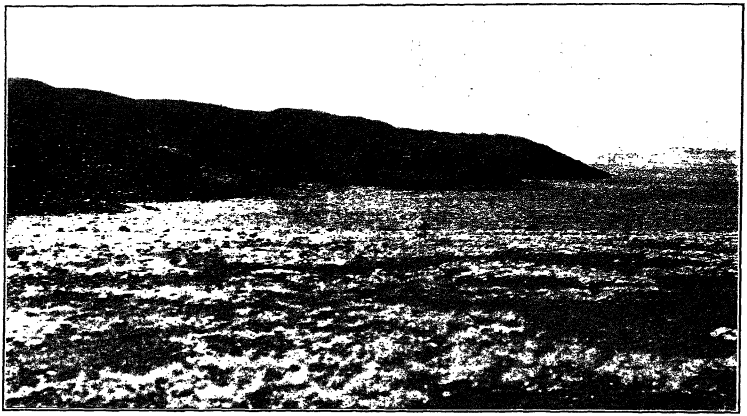

FIG. 31.—Lava flow from Sunset Peak, Ariz. (Photograph by H. S. Colton)

vesicular, with numerous bubble-holes preserved by the stiffening of the rock before the bubbles collapsed. Usually the flow of the lava has drawn these spherical holes out into ovoidal or almond-shaped cavities, which may subsequently be filled by some mineral, generally white, deposited from solution. Passing downward, the vesicles cease at a definite level, which marks the line below which the lava remained so fluid after nearly all the mineralizing vapors had escaped that all bubbles and cavities collapsed and a solid texture resulted. This is often very clearly displayed when a lava-stream is seen in cross-section, as may frequently be done in Arizona, for example.

Temperatures of Lavas. Direct measurements of temperatures have been made in the lavas of Vesuvius, Ætna, and Kilauea and found to be of about 1,000° C. (1,830° F.). In the case of the latter, the lava pool, called Halemaumau, has a temperature between 1,000° and 1,200° C. and, strange to say, the temperature is higher at the surface than below, and measurements made at a depth of 20 feet showed a drop of 100° in the temperature. The greater heat at the surface is due to reaction of the gases, one with another, and the lava-fountains, produced by the escaping gases, are most numerous when the lava temperature is rising, fewest when it is falling. How the gases contribute to the fluidity of the lava is shown by the fact that newly effused lava remains mobile down to a red heat (about 600° C.), but, when entirely cold, this same lava requires a temperature more than twice as high (1,300°) for remelting; the only difference is in the absence of the gases, which have escaped from the cold rock. A similar phenomenon has been observed in plutonic bodies; in the diabase of the Palisades, for example, are inclosures of shale torn from the intruded country rock (*xenoliths*, see p. 84) when the intruding sill was still molten. Were the magma at the temperature of its dry fusion, the xenoliths would be melted. Here again the freezing point of the magma has been much lowered by the mineralizers.

The lava extrusions and, indeed, the surface manifestations of vulcanism are of two types: the *central eruption,* in which a more or less circular crater is the seat of activity, and the *fissure-eruption,* in which the magma was forced up through relatively narrow and elongate fissures and flooded great areas. The central eruption, which nearly all existing volcanoes display, is especially associated with the mountain-making kind of diastrophism, the fissure-eruption with plateau-making. When action ceased, the fissures, filled with solidified magma, became dykes, and where erosion has sufficiently exposed them, systems of parallel and intersecting dykes remain to indicate the feeding channels.

Nearly all the continents have fissure-fed lava-plateaus on a grand scale. In North America the Columbia River lava-fields cover nearly 250,000 square miles of Oregon, Washington, Idaho, and smaller parts of adjoining states and provinces. The pre-existing topography was buried and obliterated by the floods of basalt and a flat-topped plateau resulted. In northwest India, the "Deccan traps" form an even larger lava-plateau, where the

piled-up flows, one over the other, give an appearance of stratification. In South and East Africa are vast areas of lava fields; in the latter region, following the course of the Great Rift Valley. British geologists are of the opinion that, in the Eocene epoch, a great basâltic plateau extended from Ireland to far within the Arctic Circle, a distance of more than 2,000 miles. Of this plateau only fragments remain: in Ireland, Scotland, the Faroe Islands, and in Iceland. In the latter, volcanic activity still continues and the great eruption of 1783 is the best modern instance of fissure-eruptions, "which take effect, not through a single orifice, but more or less continuously, *along an extensive fissure or group of parallel fissures*, or, at least, at very numerous points distributed along such fissures. These in a given region have certain definite directions, which we may suppose to be related to crustal strains of a large order. In Iceland one set runs northeast to southwest and another north to south. The fissures appear at the surface as long open rents (Icelandic 'gja') a few feet wide and of great depth. The Eldgja is more than 18 miles long, with a depth ranging to more than 600 feet." (Harker.) Sometimes, as in Iceland and the High Plateaus of Utah, there are numerous small cinder cones along the line of the fissure, but these are only incidental, for, usually, explosions play but a small part, or are entirely absent, in fissure-eruptions. The Absaroka range of mountains, which runs along the east side of the Yellowstone Park, is interpreted as an immense body of volcanic débris or agglomerate erupted through a great north-south fissure by explosive action. Differential weathering has shaped out of this volcanic mass the wild and fantastic topography of the "Hoodoo Country."

Interbedded or *Contemporaneous Lava Sheets* occur concordantly in a series of stratified rocks, in which they look like so many sills, from which it is not always easy to distinguish them immediately. Such lava sheets were poured out on a land surface or sea-bottom, and were subsequently covered by the deposition of sediment. If the flow was on the land, that land-area was later depressed beneath the water, but while it was on the land, it was exposed to the destructive action of the weather and may have lost all its surface portion of slag and scoriæ before the deposition of sediment began. But, as pointed out on p. 89, it will have retained the scoriæ at the bottom, it will have more or less glass in it, and the overlying bed will show no sign of heat action upon it.

An interbedded lava sheet has the same relative age as a stratum, which is determined by superposition; the sheet is younger than the bed upon which it lies, older than the bed which lies upon it. A sill, on the other hand, is younger — it may be vastly younger — than the series of rocks which it intrudes.

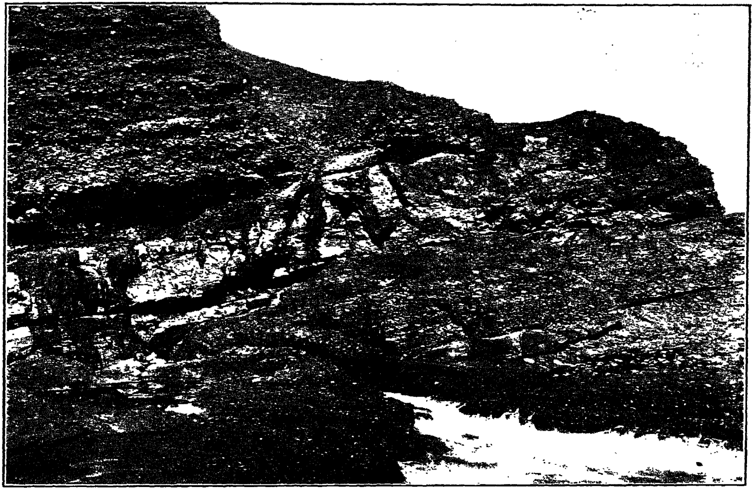

FIG. 32. — Lava flow interbedded with Old Red Sandstone, Mull, Scotland. (Geol. Surv. Gt. Brit.)

An extinct cone, like all other mountains, is slowly worn away, and we find cones in all stages of removal and degradation. In Arizona the San Francisco Mountains, north of Flagstaff, form a very picturesque group of snow-capped peaks which rise abruptly from the plateau. Though much modified by erosion, the form of this group and its component materials show plainly its volcanic nature. To the north and west of these mountains are great numbers of small, extinct cinder cones in almost perfect preservation; several of them were breached by the last eruption, the lava column pushing away one side of the cone and pouring out as a lava-stream,

until motion was arrested by the freezing of the magma. Evidently these cones cannot be of any great geological antiquity.

From Lassen Peak and Mt. Shasta in northern California to Mt. Rainier in Washington is a famous series of magnificent, snow-covered, volcanic peaks which are in the Cascade Mountains.

FIG. 33. — Pillow lava, Ordovician, Ballantrae, Scotland. (Photograph by Prof. S. H. Reynolds)

Seen from a distance, these peaks still retain their beautiful conical symmetry, but, near at hand, they have suffered much from erosion; great ravines and gorges now gash their sides and show a long period of quiescence. Some of these cones still emit hot vapors from their craters and one or more of them may possibly break out again, but this is not likely; much more probably these cones are extinct.

Volcanic Necks. The Cascade Mountain volcanic peaks exemplify the earliest stages of degradation; in the course of time, the loftiest cones are worn away by erosion until only the stump, hardly recognizable, of the volcano remains and this is called a *volcanic neck*. The neck consists essentially of the plug of consolidated lava left in the vent by the last eruption or, much less commonly, of a mass of volcanic blocks, a breccia, or agglomerate. Associated with this more or less cylindrical plug of lava may be preserved something of the lowest lava-flows, tuffs, and other

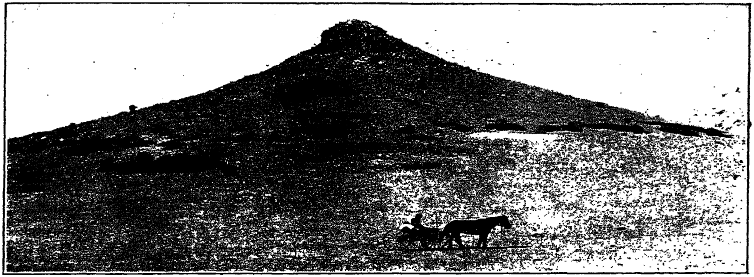

FIG. 34. — Watervale Butte, Col., a volcanic neck. (Photograph by W. T. Lee, U. S. G. S.)

ejectamenta of the ancient volcano. Great numbers of such volcanic necks, of quite late geological date, occur in Arizona and New Mexico, and they are also found in rocks of many geological periods back to very ancient ones. Figure 37 shows a hill, called Sugar Loaf, near Campbellton, New Brunswick, which is a volcanic neck dating from the Devonian period, and in the sea-cliffs, not far away, may be seen a series of lava-flows interbedded with marine strata of Devonian age.

Mount Royal, which gives its name to Montreal, is one of a remarkable series of volcanic necks placed on the same east-west line and called the Monteregian Hills. Each of these hills marks the site of an ancient volcano which, by a process of elimination, has been referred to the Carboniferous period. (F. D. Adams.) A railroad tunnel, driven through Mount Royal, has made possible a remarkably full and exact determination of the sequence of events in the volcanic chimney.

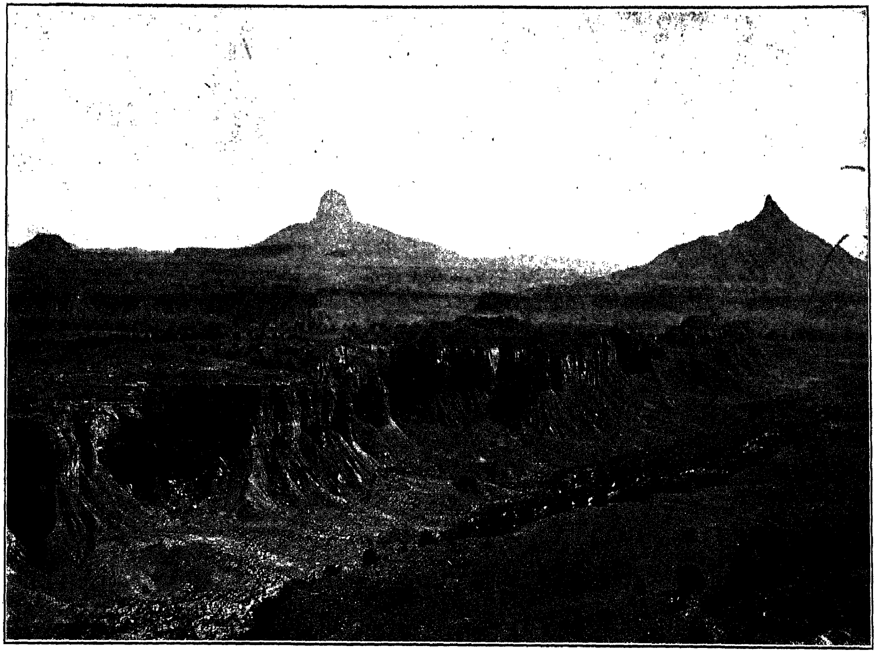

FIG. 35.—Volcanic necks, Sandoval Co., New Mexico. (Photograph by Dutton, U. S. G. S.)

The diamond-bearing shafts of South Africa, which are called *pipes* rather than necks, are usually of circular, sometimes of elliptical, cross-section, gradually contracting downward in diameter, so that they have a more or less funnel shape. The pipes are filled

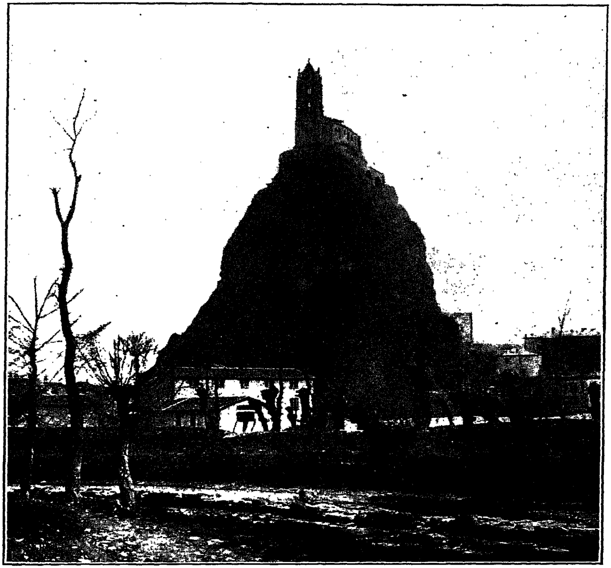

FIG. 36. — Les Roches Michel, a volcanic neck, Le Puy, Auvergne, France. (Photograph by Prof. S. H. Reynolds)

with tuff and other products of volcanic explosions, often with fragments of the country rock torn off by the explosions. Some of the material has fallen in from above into open shafts and fossil wood has been found in pipes in Scotland, Germany, and South Africa. In the latter region the pipes vary in diameter from a few yards (Kaalfontein) to ellipses with long axes exceeding 2,500 feet, as in the famous Premier Mine near Pretoria.

If these pipes are remains of ancient volcanoes, almost all traces of the cones have been swept away and, in many instances, nothing on the surface, save the finding of diamonds among the grass roots, indicated the presence of a pipe. In other instances there is a shallow pan on the surface and, in others again, a low hill, depending upon the relative resistance to weathering of the country rock and the volcanic agglomerate of the filling. Mining operations, in quest of diamonds, have followed some of the South African pipes down to depths exceeding 4,000 feet, where some of them may be traced into fissures filled with the same kind of material. In other words, the deep-seated fissures locally gave rise to explosive pipes.

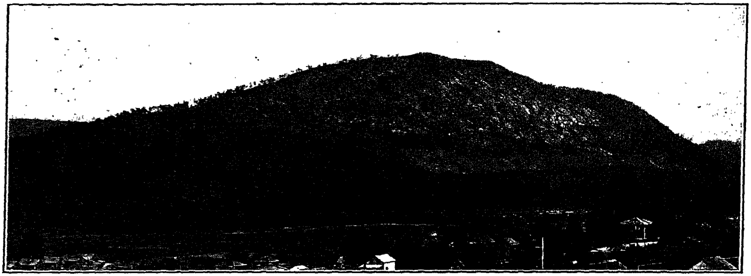

FIG. 37.—Sugar Loaf, a Devonian volcanic neck, Campbellton, New Brunswick.

Pipes of a similar character, of different geological dates and not diamondiferous, are found in southern and central Germany and southeastern Scotland and some diamond-bearing ones in Arkansas. Some of the German pipes, making a reasonable estimate of depth, have the proportions of a lead pencil. How such boreholes could be driven through thousands of feet of overlying rocks seemed quite inexplicable, until it was learned that a jet of superheated steam, or gas, when suddenly released, acts like a high-powered projectile and will perforate boiler plate one quarter of an inch thick and will cut and polish glass or granite like a sand blast. These pipes occur in surprising numbers; no less than 130 have been discovered in an area of about 300 square miles in Germany, and in southeast Scotland, near St. Andrews, 80 have been found in an area of 9 × 12 miles. Both in Europe and in South Africa

they were made without apparent reference to the large structure of the perforated strata, occurring in folded and in undisturbed beds and avoiding preëxisting faults.

In chemical and mineralogical composition the volcanic rocks are, in general, like the plutonic class and were solidified from the same magmas. Many plutonic rocks, however, have no volcanic equivalents, because of the conditions of their formation.

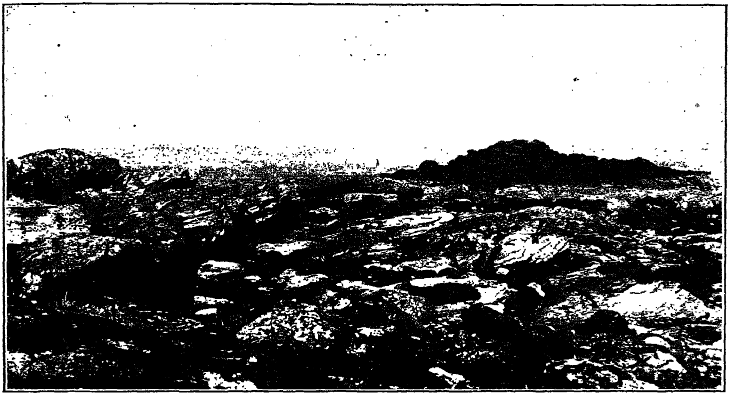

FIG. 38. — Volcanic neck near St. Andrews, Scotland. (Photograph by Prof. S. H. Reynolds)

It has also been observed that from the same vent lavas of different composition are ejected at different times and in a definite, though somewhat variable order. The scheme originally formulated by von Richthofen comprised five successive types: (1) hornblende-andesite, (2) pyroxene-andesite, (3) mica-hornblende-andesite, (4) rhyolite, (5) basalt. The succession displays increasing divergence from the initial type; there is variation in two opposite directions, and the two lines partly alternate. (1), (2), and (5) are increasingly basic and (1), (3), and (4) increasingly acid. Von Richthofen's order is frequently departed from because the initial type differs in various regions, but the "law of increasing divergence" (Iddings) is widely applicable. In the hills of Berkeley, California, the succession in the Lower Berkeleyan is andesite,

basalt, rhyolite-tuff, and then repeated: andesite, basalt, rhyolite-tuff; in the Campan one phase is omitted: andesite, basalt, rhyolite-tuff, basalt, rhyolite-tuff. In the ancient volcanic neck of Mount Royal, two distinct effusions of nepheline syenite occur, with other rocks whose relations have not been made out. (Finley.)

Fragmental Products (*Pyroclastic*) are made up of solid pieces blown out of the volcano by explosions within the lava body and, in size, range from the finest and most impalpable dust to great blocks weighing many tons. *Volcanic ash* is a misnomer because ash is the incombustible remnant of something that has been burned, but the material is so like ashes in appearance and color that the term will probably be retained. In violently explosive types of volcanic eruption, incredible quantities of ash are often produced; as, for example, in the 1902 eruption of Santa Maria, in Guatemala, or most remarkable of all, the eruption of Tamboro, on the island of Sumbawa, near Java, in 1815. When examined microscopically, volcanic ash may be determined with ease and certainty, for it is made up chiefly of fragments of glass which have the characteristically curved fracture of glass, and, in addition, there are minute fragments of mineral crystals. The ash is often carried for great distances by the wind and deposited in thick beds of remarkable purity many hundreds of miles from the source. In Kansas and Nebraska, for instance, are beds of uncontaminated ash, 20 to 25 feet thick, which must have traveled as much as 400 miles.

Torrential rainfall often accompanies explosive eruptions, and the rain, mingling with ash and dust in the air and on the ground, forms streams of hot mud, more dreaded and more destructive than the molten lava itself. Such muds, when cold, set into a moderately firm rock, which is called *tuff*, a name which is given to ash cemented and consolidated in any way. The ash may be stratified by the wind, or it may be showered into water and deposited in an unmixed state, or mingled in all proportions with sand or mud. The fresh-water deposits of Tertiary age, which cover immense areas of the Great Plains and Rocky Mountain Plateau regions, frequently contain volcanic material, sometimes concentrated in beds of more or less pure ash, much more commonly disseminated in fine particles through the strata of clay and sand. On the Pacific Coast are beds, several thousand feet thick, of marine origin, which are chiefly composed of volcanic

material and such beds contain fossils as abundantly as ordinary sediments. Indeed, beds of that character are to be classed as sedimentary; the material is igneous, the mode of transportation and deposition are sedimentary. Fresh-water tuffs often contain abundant and beautifully preserved leaf-impressions.

Scoriæ, as previously noted, are the frothy portions of the lava-stream, which solidify while still full of steam and gas bubbles. For the most part, scoriæ are formed on the surface of a lava-stream, but they also form within the crater and are blown out in larger or smaller fragments by the explosions. Small fragments, of the size of nuts, are called *Lapilli*.

Pumice is a solidified glassy froth, differing from scoriæ, which are stony, in their glassy texture and in the greater proportion of bubble-holes in it. Pumice will float and may be carried long distances in the sea by currents. Scoriæ are too heavy to be thus transported.

Volcanic Agglomerate is made up of blocks embedded in ash, and accumulated masses of these coarse materials are frequently found, but the large blocks are not transported by the wind and their distance from their point of origin is limited to the explosive trajectory, which may, however, be a distance of several miles. The heterogeneous mass of blocks, scoriæ, ash, etc., is called *volcanic agglomerate* and is often consolidated into quite a firm rock. Volcanic *bombs* are so called because of their fancied resemblance to the old bomb-shell, which was spherical and hollow. They are spheroidal, or quite irregular, in shape, stony or scoriaceous, and hollow; they are produced by small portions of plastic lava, which are blown out of the vent with a rapid rotary motion. The rotation and the viscosity of the lava fragment determine the shape of the bomb, and it is made hollow by the expansion of the gases and vapors.

Fragments are characteristically volcanic and cannot be formed under plutonic conditions, as they require free, open spaces for their formation. Their occurrence is proof, sometimes the only proof, of volcanic action at the time of the formation of the country rock. In the case of fine materials, ash and dust, they may have been transported long distances by the wind, while coarse materials imply a near-by source. Furthermore, fissure-eruptions, as a rule, are accompanied by little or no fragmental material. The fissure-eruption in Iceland in 1783 was marked by the forma-

tion of a great number of new cones along the old line of fissure and from these cones floods of basaltic lava issued, but there was some fragmental material also. As already mentioned, the Absaroka Mountains, if correctly interpreted, have been carved out of a great mass of volcanic agglomerate, which was ejected from a fissure.

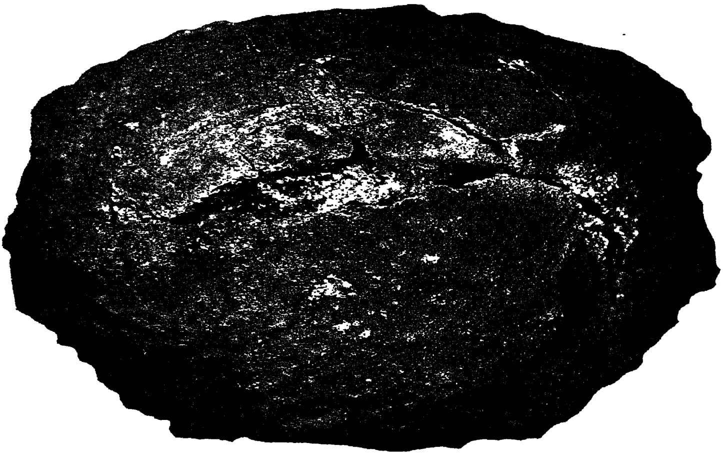

FIG. 39. — A volcanic bomb about two-thirds natural size, Sunset Peak, Ariz. (Photograph by J. R. Sandidge)

The *Gaseous Products* of a volcano are extremely important for the active part which they take in eruptions, in promoting the crystallization of lava, and in altering the country rock with which they come in contact, but they escape, for the most part, during the eruption or with the solidification of the magma and contribute but little to the permanent constituents of the rocks. "Water and various gases are present in all igneous rocks . . . which have been examined. The water amounts on the average to about 1½ per cent. . . . Some rocks contain a very much larger amount. . . . A fresh hypabyssal pitchstone has usually 5 to 10 per cent or more. . . . The other volatile constituents

found in igneous rocks are in much smaller amounts by weight. (Harker.)

The other gases and vapors emitted by a volcano vary with the temperature and degree of activity of the vent. Sulphur and sulphur compounds are sometimes emitted in great clouds, the white particles of which are often deceptively like steam in appearance. Sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) as well as hydrochloric (HCl) and hydrofluoric (HF) acids and hydrogen are common volcanic gases given off from high-temperature vents. Several substances, solid at ordinary temperatures, form volcanic vapors; besides sulphur, there are the chlorides of ammonium, calcium, iron, etc. Carbon dioxide (CO_2) is common, especially when the action is declining, and often persists after all other signs of activity have died out.

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CHAPTER VI

VOLCANIC ERUPTIONS

The phenomena of volcanic eruption are of great geological importance because they enable us to observe directly the formation of one class of igneous rocks and to infer much concerning the mode of origin of the plutonic class, the formation of which is beyond the scope of direct observation. The mode of eruption of different volcanoes and of the same volcano at different times varies so widely that, at first sight, it seems impossible that they can all be due to the same agencies. All forms of eruption, however, are connected by small gradations and constitute an unbroken series. Examples of different types may be selected as illustrative. Some vents, like Stromboli, one of the Lipari Islands northwest of Sicily, are in an almost continuous state of eruption of a very moderate kind and these are classed by German geologists as "Strombolian." Other vents, like Vesuvius, have long inactive periods of dormancy, broken by eruptions of terrible violence. In general, it may be said that there is a rough proportion between the length of the quiet period and the violence of the subsequent eruption; the longer the dormancy, the more violent the outbreak, when it comes.

Leaving aside, for the present, the characteristics of failing and dying activity, we may begin the examination of eruptions with the *explosive type*, in which little or no lava is ejected. In the Japanese volcano Shirane, the eruption of 1882 consisted of a single tremendous explosion without lava or ash, as did also the eruption of another Japanese vent, Bandai San, in 1888, which lasted only two hours and blew away the greater part of the mountain, more than 2,000 feet high; in these eruptions no volcanic ash, lava, or products other than gases were emitted, and the cause of the explosion may have been different, as will be shown later, from that of other volcanoes.

Vesuvius was known to civilized men for many centuries before the Christian era, but all tradition of its volcanic nature had died

out before the first recorded eruption of the year 79 A.D. This has been made particularly famous not only because of the destruction and burial of the ancient Roman cities, Herculaneum, Pompeii, and Stabiæ, but also because of two letters, describing the eruption, written to Tacitus by the younger Pliny, who witnessed the catastrophe from Misenum, twenty-five miles west of the mountain. That first historic outbreak of Vesuvius differed from subsequent ones in being purely explosive, ejecting enormous

FIG. 40. — Eruption of Vesuvius, April 26, 1872. (U. S. G. S.)

quantities of fragmental products, but no lava. Herculaneum was buried deep under a mud flow, which set into quite a firm rock, so that the excavation of that city has been a very slow and costly work.

Pompeii, which is nearly six miles from the crater, was buried under loose material to a depth of thirty feet or more. The lower part of this débris is made up of lapilli, small, nut-like, rounded fragments of scoriæ, above which is a much thicker layer of fine ash. So enormous was the quantity of ash and dust ejected, that the sun was hidden and, at Misenum, the darkness, in Pliny's phrase, was "not as on a moonless, cloudy night, but as when the

light is extinguished in a closed room. . . . In order not to be covered by the falling ashes and crushed by their weight, it was often necessary to rise and shake them off." Since that first recorded outbreak, Vesuvius has had many eruptions, with periods of quiescence between; sometimes the periods of dormancy have been several centuries in duration, but there is no regularity in the alternations of dormancy and activity.

Many of the East Indian volcanoes have been characterized by the extreme violence of their explosive outbreaks. The most celebrated of these is the eruption of Krakatau in 1883. This is a small island in the Straits of Sunda, between Java and Sumatra, and little was known of its history except that it had been in activity in 1680. In May, 1883, a cloud of steam was seen over the vent and in August came the series of gigantic explosions, which sent a wave of barometric disturbance around the whole world, reaching Berlin in ten hours. The island was so completely destroyed that hardly one third of it remained, and water, 100 to 150 fathoms in depth, now covers what formerly was land. No lava was emitted, but an incredible quantity of fragmental material was blown out and ashes were distributed over 300,000 square miles, while the quantity of pumice floating in the sea was so great as to block navigation. Most remarkable of all the phenomena of this wonderful eruption was the gradual diffusion of the finest dust over the entire earth, remaining suspended in the upper atmosphere for many months and, throughout the winter of 1883–84, causing extraordinarily brilliant red sunsets, in some places green. The loss of life directly due to the outbreak was not great, but the disturbance of the sea-bed produced immense waves along the coasts of Java and Sumatra, which drowned 36,000 people.

On the lands and islands around the Caribbean Sea, the year 1902 was an *annus mirabilis*, so far as earthquakes and volcanic paroxysms are concerned. The most remarkable of these outbreaks was the eruption of Mont Pelé in the island of Martinique, which had been quiet since 1857. After certain preliminary symptoms, such as earthquakes and ash-clouds, the first great outbreak came on May 8, when the terrible "hot blast" (*nuée ardente, Glutwolke*), an immense cloud of hot vapor, mingled with glowing particles of ash, rolled down the valley of the Rivière Blanche upon the city of St. Pierre, instantly destroying the town and all of its 30,000 inhabitants. The velocity of the air set in motion by

the descending blast was so great that it hurled from its pedestal, to a distance of forty feet, the great iron statue of Notre Dame de la Garde, which weighed several tons. In an instant St. Pierre was reduced to the condition of Pompeii — which the photographs immediately suggest.

A peculiar feature of Mont Pelé was the great obelisk-like spine of solidified lava which filled the crater and was gradually pushed up to a height of 1,800 feet, but was continually losing material by scaling from the sides; eventually, it disintegrated altogether.

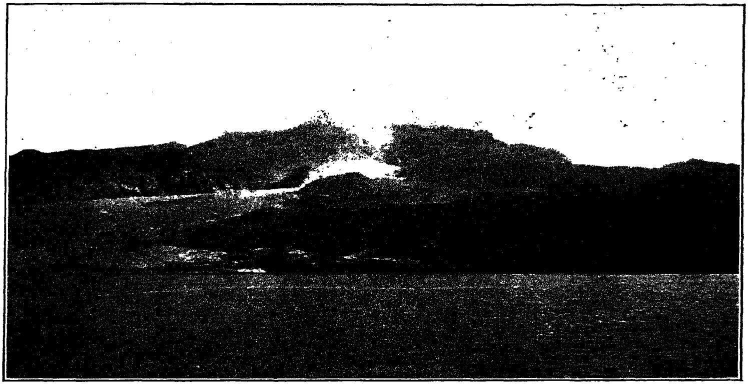

FIG. 41. — Mont Pelé, Martinique, from the sea. (Gift of Mrs. Cecil Fisher)

Observers differed as to whether this spine was the old lava plug which had filled the vent since the last eruption or was newly ascended and extremely viscous lava. After the great catastrophe of May 8, 1902, Mont Pelé had a long succession of eruptions up to September 16, 1903; some of these, especially the last, were almost as violent as the first one, and these were all carefully observed and photographed.

On the adjoining British island of St. Vincent, the volcano called La Soufrière, the last violent eruption of which had been in 1812, began to show signs of renewed activity in a succession of earthquakes in February, 1901, which increased in violence till May 6,

1902, when there was a series of tremendous explosions and, on the following day, the eruption became continuous and the frightful "hot blast," or *nuée ardente*, rolled down the mountain like an avalanche, causing the loss of 1,400 human lives. As there was no large town in the track of the blast, the destruction of life was far less than that caused by Mont Pelé, but the explosions were actually more violent and ejected a greater quantity of material, a finely divided ash. The eruptions were repeated at intervals and with different degrees of violence for considerably more than a year.

In the same year Central America was the scene of much volcanic activity. In Nicaragua there was an unimportant eruption of Masaya (June 25); and Izalco, in Salvador, after a pause of more than a year, began erupting again on May 10, but this eruption was not of the explosive type and produced streams of lava. Far more violent was the outbreak of Santa Maria in Guatemala, which had been regarded as extinct, because it had been entirely inactive since the discovery of the country by Europeans. The eruptions began on October 24 and continued, with diminishing violence, for more than a year; an incredible quantity of ash was thrown out, covering several hundred thousand square miles and, near the mountain, burying houses to depths of fifty feet or more.

After the great eruption of 1902, the first one in historic times, a few slight signs of activity continued, sulphur odors being perceptible as late as 1911. In the summer of 1922 there was a renewal of the outbreaks; at first, moderate discharges of ash and dust were followed by the formation of a lava dome within the crater, which gave off clouds of vapor and changed its form continually by scaling off from the outside, recalling the spine of Mont Pelé. (Sapper.) Diminishing action continued with long intervals of quiescence, the last minor outbreak being on May 14, 1928, until, on the night of November 2, 1929, there was a violent eruption with discharge apparently from the foot of the lava dome of a "glowing cloud," similar in character but far less violent and destructive than the famous cloud of Mont Pelé. The contrast between the three great eruptions of Santa Maria in the present century is very striking; the first one, in 1902, as is usual after a long period of dormancy, was purely explosive, extremely violent, and discharging great quantities of volcanic ash. The outbreak of 1922 was notable for the rise of the lava dome within the crater, much like the "spine" of Mont Pelé. Apparently because of this

obstruction, the outbreak of 1929 resembled that of Mont Pelé in the expulsion of the glowing cloud.

One of the major volcanic eruptions of history is that of Katmai in the Alaska Peninsula in June, 1912. This also was an explosive eruption, without lava, but in the quantity of ash ejected exceeding Krakatau by 50 per cent, according to estimates. "The Valley of Ten Thousand Smokes" (so widely celebrated as a most remarkable display of volcanic activity) is due to the blanket of hot ash with which Katmai has filled it.

In quantity of material ejected, the most tremendous of all known eruptions was that of Tamboro in 1815. This volcano is situated on the island of Sumbawa, near Java, and had been considered extinct until 1814, when a series of minor explosive eruptions began. The explosions, which came every 15 minutes, reached their maximum on April 10, 1815, and continued, with diminishing intensity, until the following July 15. No lava was emitted, only fragmental products, for the most part ash, but with some glowing blocks and scoriæ. For a radius of forty miles around the volcano every village was buried out of sight and, according to Verbeek, the amount of material ejected reached the unprecedented total of 150 cubic kilometers, which is three times that of the next greatest known eruption, that of Coseguina, Nicaragua, in 1835.

A very interesting example of what would seem to have been the moribund phase of explosive action is afforded by Lassen Peak, in northern California, which was in progress for three years, 1914–17, and only once during that time reached a temperature of red heat. The eruption began on May 30, 1914, with an explosion in the summit crater, and the explosions were repeated at intervals of four or five days through the summer and autumn, perhaps in the winter also, but the summit of the peak, which has an altitude of 10,000 feet, is veiled in clouds during the winter season. In May, 1915, "came three days of terrific activity, during which the dust cloud reached a height of 25,000 feet above the summit of the mountain and blocks the size of a man's hand were thrown for ten miles." (Day.) The old lava plug, which filled the chimney of the vent, was raised three hundred feet, level with the rim of the crater, and beneath it two tremendous, horizontal blasts burst out at the northeastern point of the cone. These blasts completely destroyed all vegetation for a distance of four miles, but

FIG. 42.—Lassen Peak, Calif., mud flow on northeast slope. (Courtesy of the Chief of Air Corps, U. S. Army)

they caused no forest fires. Red-hot ejecta were seen only once and the blocks thrown out were not hot enough to melt the snow. The activity died away gradually, with a few minor explosions in 1916 and a final one of considerable violence in May, 1917. The likeness of these eruptions to those of Mont Pelé is obvious, but with the striking difference of temperatures displayed. The material ejected from Mont Pelé was exceedingly hot, destroying the population of St. Pierre in a moment's time and setting ships in the

FIG. 43.—Interior of crater of Kilauea, Halemaumau Pit, looking southwest. Two lava lakes and islands, Sept. 7, 1920. (Photograph by T. A. Jaggar)

harbor on fire, while at Lassen Peak the ejecta were so cool that no forest fires resulted from contact with them.

A radically different type of volcanic eruption is that seen in the Hawaiian Islands, all of which are volcanic and built up from the floor of the deep sea. The group is isolated in the Pacific Ocean, and the several islands show a linear arrangement in two parallel lines. Only two of the vents, Mauna Loa and Kilauea on the island of Hawaii, are known to be active at the present time, and the latter has been observed and studied in a manner that is equaled only in the case of Vesuvius. In the recorded history of Kilauea, there have been violent explosions, but the ordinary activity of the volcano produces only lava of an exceptionally thin and fluid sort, without scoriæ or ash. In fluidity, the lava is often compared to honey. The crater of Kilauea, which opens on the flank of Mauna

Loa, is a great pit, or *caldera*, and is subject to frequent changes of form and dimensions, at present measuring about 3 miles by 1 mile; an inner crater, called the "Lower Pit" (which is approximately one half the diameter of the outer pit), is floored with lava, solidified, so that it may be walked on safely, and in this Lower Pit is the lava lake Halemaumau, the activities of which display such a celebrated spectacle and are remarkably different from time to time.

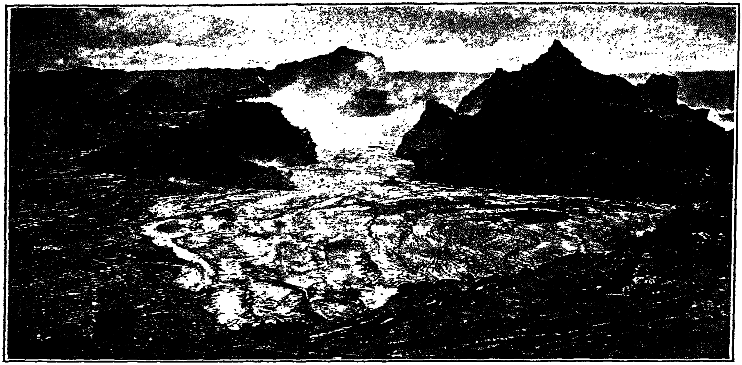

FIG. 44. — Interior of Halemaumau, looking southwest, Sept. 20, 1921. Pool cracking up and crusts sinking; crags are part of lava column. (Photograph by T. A. Jaggar)

In 1912, for instance, Halemaumau measured approximately 800 by 500 feet, and varied in surface temperature from 950° to 1,185° C. There was also great difference from time to time in the quantity of gas discharged from the fluid lava. A photograph taken on July 3 showed more than 1,100 fountains of lava caused by gas bubbles, while, at other times, the fountains were few and occasional, and the important observation was made that when the discharge of gases was most active, the lava temperatures were highest. At times, as happened in 1924, the lava lake is completely emptied by draining away through subterranean channels. In the summer of that year, gases were explosively discharged from the empty basin and these explosions enlarged the crater to a diameter of 3,500 feet and a depth of 1,500 feet, which was more

than twice as deep as had ever been observed before. In May, 1924, there was a violently explosive eruption, in which many blocks of all sizes had been thrown out. These blocks were of old lava, porphyritic in texture, almost free from bubbles, and entirely different from the observed flows typical of Kilauea.

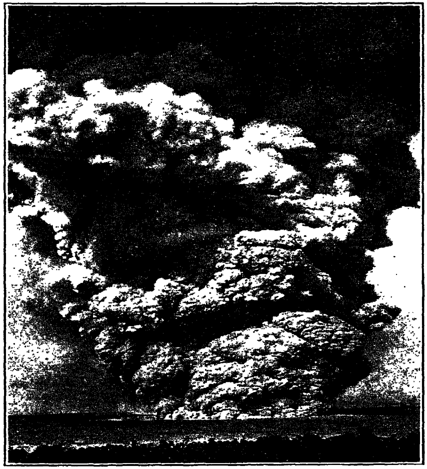

FIG. 45. — Eruption of Kilauea, May, 1924. (Photograph by Tai Sing Loo, Hawaiian Volcanic Observatory.)

"At one side of the great bowl, about 600 feet above the bottom, was an area some 500 feet in its transverse diameter and more than 100 feet thick, which showed here and there a trace of red at night. . . . Above it on the rim a hot air-current was continually depositing fine flakes of freshly oxidized, iron-bearing scale. This may have been one of the feeders of the lava lake. It was certainly the hottest spot left exposed in the empty basin. Another smaller area in one corner of the bottom was distinguished by a half-dozen roaring gas outlets, whose throats glowed red at night. This may have been a smaller feeder. When the lava began to return to the pit in July, it spouted out from a point high up on the talus pile on the opposite side of the basin in a fountain 175 feet high. This must have been from a third feeder. No others have so far been discovered." (Day.)

In July, 1919, Dr. Jaggar had observations of the level of the lava surface in Halemaumau taken at intervals of twenty minutes throughout the month, and the oscillations of level due to the tidal action of the sun and moon amounted to only an inch or two in oscillations of several feet. (E. W. Brown.) This indicates that the subterranean reservoirs of magma cannot be very large.

These newer observations call for a changed conception of Kilauea. Instead of a flask-like chamber, extending upward into a narrow neck filled with lava, it would seem that there must be several magma reservoirs with separate feeders into a "central collecting tube," and that the several chambers are at different temperatures and pressures and with a content of different gases.

Despite the situation of Kilauea, which is an opening on the flank of Mauna Loa, the two vents appear to be quite independent of each other. Mauna Loa is an immense, flat cone, with a diameter of forty miles at sea-level and its summit rising nearly 15,000 feet above that level. The lava is of the same extremely fluid kind as that in Halemaumau and the eruptions yield hardly any fragmental material. Lava is very rarely ejected from the crater, the enormous pressure of the molten column ruptures the cone and breaks through at levels which differ in different years. One of the greatest recorded outbreaks is that of 1868, when the lava broke through the cone at about 3,000 feet above the sea and rose in great, fiery fountains to heights of 1,000 feet or more. Ships passing at night reported that the whole eastern side of the island seemed to be on fire. The extremely fluid lava from this vent flows in streams forty or fifty miles to the sea, in which it breaks up into a black sand.

FIG. 46. — Lava froth fountain, 200 ft. high, southwest rift of Mauna Loa, Oct. 25, 1924. (Photograph by T. A. Jaggar)

Lava streams from Kilauea have never been known to flow over the crater walls, but, in addition to the explosive eruption of 1924, there have been several others which were even more violent. Very imperfectly known is the eruption of 1789; it was evidently a tremendous explosion, or series of them, which hurled out great masses

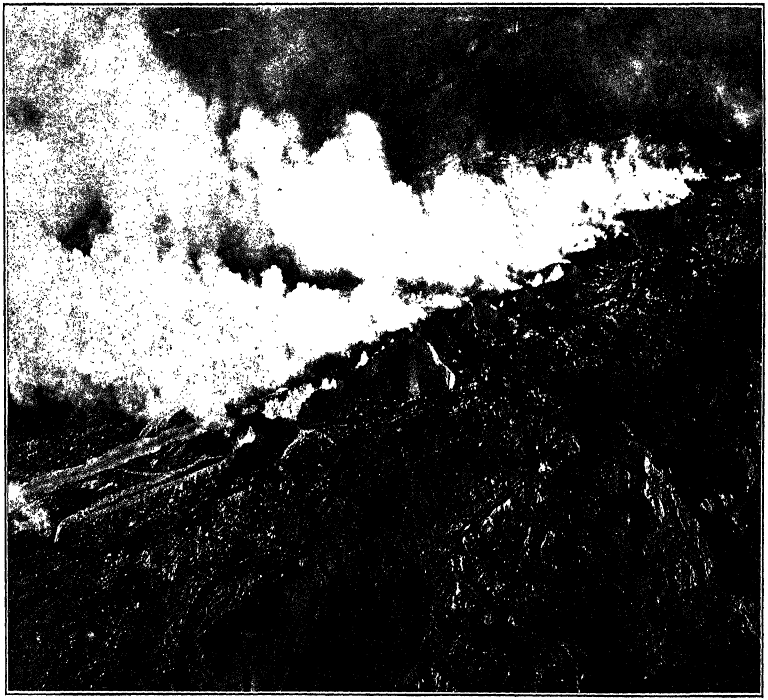

FIG. 47.— Mauna Loa, fissure eruption, with line of craterlets, April 18, 1926. (Photograph by 11th Photographic Section, Air Corps, U. S. Army)

of fragmental products. The tuffs which crown the summit of the outer crater, or caldera, are deposits of ash, referred to the explosions of 1789. In the years 1848–55, Kilauea was comparatively quiet and the supply of hot gases from below was insufficient to keep the lava in Halemaumau in a fluid state. Consequently, the lava pool was "frozen over," covered with a crust of consolidated lava, which rose in a vaulted dome to a height of 300 feet and, in August, extended above the level of the lower points of the crater. In the following spring, the summit of the dome burst open and fountains of molten lava sprang to heights of 45 to 50 feet, with very violent detonations. In the succeeding years the dome disappeared.

FIG. 48. — Ngaranhoe volcano, New Zealand, eruption of May 18, 1926. (Gift of J. Greenlees, Esq.)

Vents from which extremely viscous lava is extruded form lava domes which have no crater and do not flow, so that the domes have exceedingly steep, even vertical sides. Several of these lava domes have been observed in process of formation in modern times. A dome arose

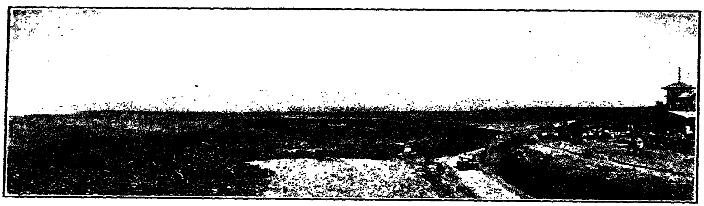

FIG. 49. — Cone of Mauna Loa, looking west from Volcano House, Kilauea. (Photograph by Gartley, Hawaiian Volcanic Observatory)

in the crater of Tarumai on the Japanese island of Hokkaido in 1909. The Bogosloff Islands rose from the sea to the north of the Aleutian Islands, as lava domes in 1796, 1883, 1906, and 1907, but the later ones were destroyed by explosions. Of the more ancient domes a classical example is the Puy de Sarcoui, in the

FIG. 50. — Mauna Loa, outbreak of lava froth and gas, May 19, 1916. (Photograph by H. O. Wood, Hawaiian Volcanic Observatory)

Auvergne, France, which is a dome thrust up between two volcanoes and invading the craters of both. Many other instances might be cited, but in each case the lava is of the extremely viscous kind, usually an andesite.

The types of eruption exemplified by the unimaginably violent explosions of Krakatau and Katmai and the non-explosive lava-flows of the Hawaiian volcanoes are the extremes of volcanic action. Much the greater number of volcanic eruptions are of intermediate or mixed character, such as is displayed in most of the known eruptions of Vesuvius, lava-streams flowing out from the crater or

bursting through the sides of the cone while explosions hurl out fragmental solids, scoriæ, bombs, ash, and dust. During historic times, Vesuvius has had long periods of dormancy. With the exception of a moderate outbreak in 1500, the volcano was inactive for nearly 500 years, from 1139 to 1631, but since the latter date, the eruptions have been much more frequent. As a rule, the

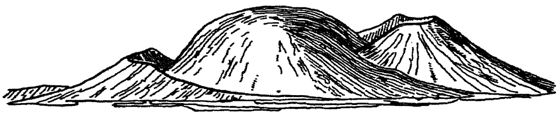

FIG. 51. — Puy de Sarcoui, a lava dome between two cinder cones, Auvergne, France. (Scrope)

more violent outbreaks have ended long periods of quiescence, but one of the most notable eruptions, that of 1906, came after a short resting time.

Vesuvius. One of the greatest, if not the very greatest of the eruptions of Vesuvius, after the Plinian outbreak of 79, was that of 1906, of which a very thorough study was made by Mr. F. A. Perret, whose account may be briefly summarized. There had been comparatively mild action, both in explosions and in lava-flows which burst through the cone a little below the summit in 1904 and 1905, the flows continuing for more than 10 months, but these manifestations were but preparatory to the great paroxysm which began April 4, 1906, and went through three phases. (1) *The Luminous, Liquid Lava Phase:* While immense clouds of ash rose from the crater and lava burst through the cone down to a level only 2,000 feet above the sea, there were great lava fountains projected upward from the crater. "Another uprising of highly incandescent magma to the upper portions of the conduit was indicated by the truly marvelous brilliancy of the ejected material, which began to clothe the greater part of the cone, while even higher above the crater arose the great geyser jets [of lava] in rapid succession" (p. 40). "The pillar of liquid — maintained continuously at a height of several kilometers by multiple projections from parts of the magma column within the conduit — illumined the Gulf of Naples from Capri to Miseno" (p. 41). Torrents of lava also issued from the vents previously opened through the flanks of the cone. On April 8, the upper parts of the cone

fell *outward* and there followed almost immediately the (2) *Intermediate Gas Phase,* of which the outstanding characteristic was "the paroxysmal emission of gas. The conduit had been cleared of lava and through it rushed, with a terrible roar, like that of Niagara, a continuous blast of gas, like the blowing off of steam from a boiler, rising to a height of 8 miles. At 3 P.M. of the same day, this phase reached its culmination. Some ash was swept out with the blast, but relatively negligible in quantity." (3) *Dark, Ash Phase:* "The morning of April 9 revealed the emission of a truly imposing volume of ash, apparently from a greatly widened crater and with greatly reduced pressure of gas. This phase continued with fluctuating, but diminishing violence, for nearly 3 weeks. When it was again possible to climb the mountain to the summit, it was found that the crater was greatly enlarged and that nearly 500 feet had been removed from the top of the cone."

Stromboli, 1930. The usual and almost continuous activity of this volcano, which has been going on for 2,000 years or more, consists in the ebullition of a column of very liquid lava which rises and falls as the gas globes form and escape. The action is so gentle that it is safe to sit in the crater and watch it, but this gentle action has, from time to time, been interrupted by violent paroxysms of very destructive character. In the present century Stromboli broke out violently in 1907 and again in 1912 and 1915; in June, 1921, there was an outpouring of lava and sulphur dioxide gas from the crater, which temporarily drove most of the population (2,800) from the island. September, 1930, witnessed another violent outburst of an unusual kind. Partly by hydrostatic pressure and partly by melting its way, a flood of lava burst out at the base of the cone, while a succession of violent explosions in the crater blew off the top of the mountain.

Classification of Recent Volcanoes

German geologists recognize seven types of volcanic eruption, which have been named from vents now active; the same vent may belong to different classes at different times.

1. *Hawaiian Type,* exemplified by Mauna Loa and Kilauea; quiet effusion of lava, but sometimes there is explosive activity.

2. *Strombolian Type,* named from Stromboli, one of the Lipari Islands, which has been active almost uninterruptedly for 2,000

years or more. The action is rhythmical; at intervals of ten to twelve minutes, the very fluid lava rises almost to the edge of the crater, a gas bubble forms on the surface and bursts explosively, sending out a shower of lava drops, scoriæ, bombs, and crystals of augite. Then the lava column sinks down out of sight. From time to time, the rhythmical activity is broken by violently explosive paroxysms.

3. *Mixed Eruptions*, such as most volcanic eruptions are, eject quantities of fragmental material explosively and also lava-flows.

4. *Vulcanian Type*, named from the island Vulcano, one of the Lipari group. The magma is very viscous, and rapidly forms a crust between explosions; fragmental products, ash, scoriæ, and bread-crust bombs, are thrown out, but there are no lava streams.

5. *Peléan Type*. The crater is filled with a lava plug, which is raised by gas pressure from below, and the hot blast is discharged from the side of the plug and rolls down the cone like an avalanche. Lassen Peak displayed a moribund stage of this type.

6. *Plinian Type*. The first historic eruption of Vesuvius is so associated with Pliny the Younger, because of his famous descriptive letters to Tacitus, that the use of his name for such outbreaks is appropriate. The especial characteristic of the Plinian type is the extraordinary violence and brief duration of the main paroxysm, which may be preceded and followed by moderate explosions. The material ejected, often of incredible quantity, is all fragmental, no lava whatever reaching the surface as such. Referable to this type, beside the first known eruption of Vesuvius, are Tamboro (p. 111), Krakatau (p. 108), Santa Maria in Guatemala (p. 110), and Katmai (p. 111). Coseguina in Nicaragua, a volcano which had been regarded as extinct, broke out in 1835, in one of the most tremendous catastrophes in the history of vulcanism. Other examples might be cited.

7. *Semi-volcanic Explosions* are those which are believed to be due to the sudden access of large bodies of water from the surface to hot volcanic foci. There is, of course, no lava and often no ash or scoriæ. The Japanese volcanoes of Shirane in 1882 (p. 106), Bandai San in 1886 (p. 106), and Azuma San in 1893 are assigned to this type, as are also Gelungung in Java, 1822 and 1840, perhaps Turrialba in Costa Rica, 1864–66, and others. Some of the explosions of Lassen Peak (p. 111) are believed to be of this character.

Omitting for the present the semi-volcanic explosions, the six classes of eruptions listed above seem to be radically different from one another and yet, not only are they all connected by intergradations into a continuous series, but one and the same vent may, at different periods, be referable to different types.

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CHAPTER VII

VOLCANIC CONES — NEW AND SUBMARINE VOLCANOES — DISTRIBUTION

Essentially, a volcano is a pit, or opening, of unknown depth into the earth's interior. This is exemplified by Kilauea, the lava of which never overflows the edge of the crater; the rare explosions, with the ejection of ash, have failed to form a cone. Nearly all

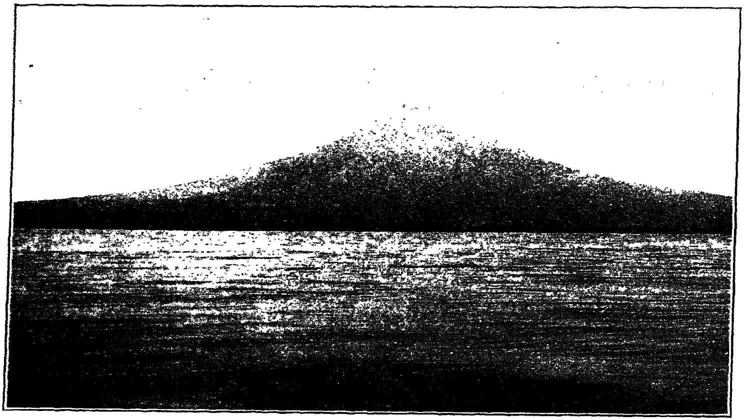

FIG. 52. — Mayon, a cinder cone, Philippine Islands. (U. S. G. S.)

volcanoes, on the other hand, are in conical mountains which are built up, often in colossal dimensions, by the materials ejected from the vents. The form and proportions of the cone are determined principally by the character of the materials thrown out, but also by the nature of the activity itself, whether quiet or ex-

plosive, whether constant or shifting in position. Volcanic cones are grouped in three classes:

1. *Lava Cones* are composed entirely of lava sheets and streams and have been built up by the piling of one lava flow on another. The shape of a lava cone is conditioned by the degree of the lava's fluidity and the distance to which the streams flow before coming to rest. The great Hawaiian cones are built up of flows of a lava that is exceptionally fluid and hence the cone is very low in proportion to its diameter, and the slope of its sides is extremely

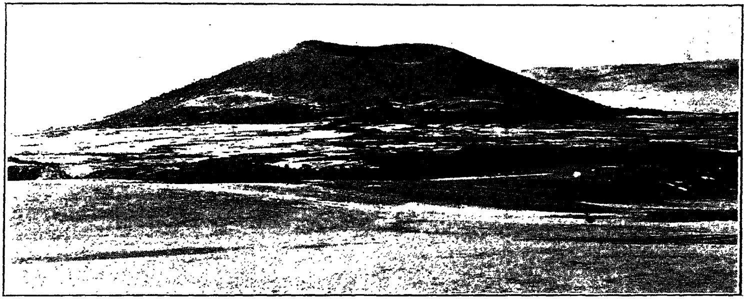

FIG. 53. — Mt. Capulin, N. M., a truncated cinder cone. (Photograph by W. T. Lee, U. S. G. S.)

gentle. Mauna Loa, for instance, rises from deep water (3,000 fathoms) and is 200 miles in diameter at its base on the sea-floor and 40 miles at sea-level, above which it rises to a height of nearly 15,000 feet. The slope of the flanks is only 3 per cent. The German expression for cones of this description is *Shield Volcano* (*Schildvulkan*), because its shape recalls that of a shield, with convex surface, lying on a table. (See Fig. 49.)

Cones made of extremely viscous lava are the lava domes described above, which have almost vertical sides and no crater. This shape has been well imitated by forcing stiff clay through a small hole.

2. *Cinder Cones* are built up of fragmental material blown out of the vent and accumulating as it falls, according to the angle of rest. Hence, coarser materials form a more steep-sided cone than does ash. The form of a cinder cone is very perfectly imitated by

blowing a jet of sand through a hole in a table. Even dumping a load of sand from a cart often makes a beautiful cone. Pure cinder cones with no admixture of lava are mostly small, because built up by short-lived activity. The great majority of volcanic cones are of the third class.

3. *Mixed Cones* are formed both of fragmental materials and of lava-flows, but the former are greatly in excess and determine the form. Many cones, notably the famous ones in the Andes of South America and in the Cascade Mountains of the northwestern

FIG. 54. — San Francisco Mountains, Ariz., looking northeast, a group of much eroded volcanic cones. (Photograph by Carson)

United States, are extremely beautiful from their graceful outlines and their caps of snow. Fuji-San, the sacred mountain of Japan, is a volcanic cone of exquisite grace and appears in most Japanese decorations. The lava is present not only as flows, but also as dykes, where the cone was breached by the pressure of the lava column, the lava escaping at various levels below the crater. The fissures thus made are filled with lava, which consolidates on cooling.

The cones of all three classes show a false stratification, being made up of successive layers piled up one over the other, as deposited by the successive eruptions. In the lava cones the layers are less distinct, especially if the intervals between eruptions have not been long enough to allow much weathering. In the cones of the cinder and mixed types the layering is distinct.

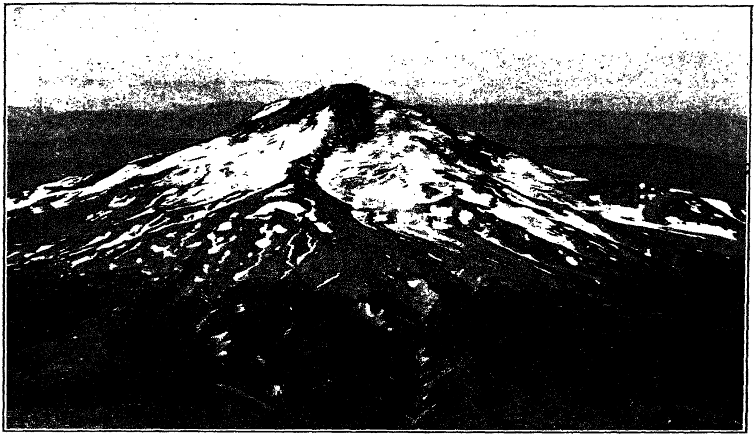

FIG. 55. — Mt. Hood, Ore., mixed cone, much dissected. (Courtesy, Chief of Air Corps, U. S. Army)

FIG. 56. — Crater Lake, Ore. (Courtesy, Chief of Air Corps, U. S. Army)

Volcanic cones, like all other features of land surfaces, are subject to the destructive attack of the atmosphere and, in the case of islands, of the sea also. So long as activity continues, the ravages of the eroding agents are repaired by the deposition of freshly erupted materials, but, as we have already seen (p. 97), the cones of extinct vents are more or less rapidly worn away, it may be to the very roots. By extreme violence of eruption, volcanoes often

FIG. 57. — Dyke of porphyry, cutting rhyolite, Glen Coe, Scotland. (Geol. Surv. Gr. Brit.)

destroy a great deal of their own cones. Immense explosions, such as those of Tamboro and Katmai, blow off the top of the mountain and form a vast *crater ring*, or *caldera*, within which a quieter renewal of activity may build up a smaller cone. Tamboro lost more than 4,000 feet of its height and the crater ring is nearly five miles in diameter. Vesuvius is half inclosed by the partial ring of Monte Somma, the original cone, which was half blown away by some unrecorded, prehistoric paroxysm and Vesuvius was built up by subsequent eruptions. Half of the cone of Bandai

San was blown away by the explosion of 1888, and Krakatau destroyed nearly the whole island on which it stood. Crater Lake in Oregon, so wonderful a spectacle that it has been made a National Park, is also a caldera or crater ring, which has, however, been produced in a manner different from the instances just cited. That there must formerly have been a high volcanic cone at that spot is demonstrated by the glacial striæ, which require a mountain above the present crater ring. Had the top of the cone been blown off, as has so frequently happened, an immense quantity of débris would have been distributed over the surrounding country, but there is no such débris and some other explanation for the removal of the cone must be sought. In all probability, the cone was undermined by remelting of the solidified lava and then collapsed into the chimney, where it was remelted in turn and drained away through subterranean channels. Something of this sort was observed in the 1906 eruption of Vesuvius, where the remelting of old lava by the hot gases was seen and the top of the cone was removed, partly by outward explosions and partly by internal avalanches. Wizard Island is a "conelet" of scoriaceous materials, a cinder cone which marks the last and greatly diminished phase of activity of this vent.

New Volcanoes

A considerable number of new volcanoes have broken out within historic times in places where there were no vents before. This has happened both on land and on the bottom of the sea, often resulting in the birth of new islands. In 1538, near Pozzuoli in Italy, the ground fissured, exposing red-hot lava, and from this fissure great masses of fragmental products were ejected, but no lava appeared on the surface. The action continued for a week and then died out, but sufficed to build up a cone 440 feet high of gray pumice blocks, which is called Monte Nuovo and is hardly distinguishable from the other cones of the Phlegræan Fields, extinct in Vergil's day.

In Mexico there is a wide plain between the well-known volcanoes Toluca and Colima, and on this plain, thirty-five miles from the nearest vent, a new volcano broke out on September 29, 1759.

Jorullo, 1759, is of especial interest, chiefly because its history is so fully known and because it is a "modern instance" of a

fissure eruption, on a small scale. This little group of volcanic cones is in the State of Michoacan and stands in an amphitheater in the southern slope of the Mexican plateau, where there were no active vents, but some extinct volcanic hills were known. The site of the outbreak was a hacienda famed for its fertility and called by the Indian name Jorullo, which means paradise. The farm-bailiff, Sayago, was an eye-witness of the outbreak and made reports to the Spanish Viceroy. Near the end of June, 1759, the people at the farm were alarmed by subterranean noises which continued, at intervals, until September 27, when the sounds became very loud and were accompanied by earthquakes, which continued almost uninterruptedly for ten days. On September 29, at 3 A.M., a dark cloud rose from the bottom of a ravine about one-half a mile southeast of the hacienda, soon followed by "roaring flames." The steam cloud condensed into rain and formed mud streams with the ash and dust expelled from the fissure; in the course of the day, the farm buildings were destroyed and the land ruined by the showers of mud. A more violent outbreak from October 2 to 8 produced such quantities of ash that the entire population of La Guacana, some 5 miles to the west, moved away and the ash was carried 50 miles by the wind. October 8 and 9 incandescent bombs accompanied the continuing clouds of ash. From October 14 only dry ash was ejected, no steam or mud, and the earthquakes, darkness, and downpour of rain were worse than before. Sayago left the district and we hear no more of him after November 13, by which time a volcanic cone 820 feet high, with a circular crater, had been built up. This first stage of Jorullo's history would seem to have been entirely explosive, with no lava extrusions, and definite mention is made of only a single cone. After Sayago's departure, there are no contemporary accounts of the volcano's activity, but, according to tradition, the violent eruptions continued until February, 1760, and again, during four years, there was violent activity from time to time.

From 1764 to 1775 was a time of failing activity, and there has been no renewal since the latter date. According to a report of Governor Bustamante, the three high cones were in 1766 much as they are at present. There are four or five cones, which all lie in the same north-northeast and south-southwest line, evidently placed on the same fissure, which is about two and one-half miles long. The main cone, called Jorullo, is 1,300 feet high; the

others, in Spanish, *volcancitos*, are very much smaller. One such minor vent, Volcancito del Norte, is north of Jorullo, and three others, Volcancito de Enmedio, Volcancito del Sur, and an unnamed one are on the south. All of the cones are breached on the southwest side by lava-flows, which unite into a great sheet some five square miles in area and nearly 350 feet thick. This is locally known as the Malpaìs (bad country) and is made up of several separate lava-flows, the number of which is variously estimated at four to six by different observers. Dr. Gadow, whose posthumous report is the latest on the subject, suggests that the lava-flows began in 1764, when, according to tradition, the eruptions reached their acme of violence.

Most of the volcanoes which first appeared within historic times have had but a brief period of activity, but Izalco, which arose in 1793 on the west coast of Central America, north of the city of San Salvador, has been almost continuously active till the present time and has built up a cone 2,000 feet high. Preliminary activity in the area began in 1769, but the present vent opened in 1793, throwing out immense quantities of scoriæ, followed by lava-flows, which continued for five months.

In Nicaragua, several new vents opened among the Maribios volcanoes in the course of the nineteenth century, notably in 1850 and 1867. In both of these the new openings were made explosively and fragmental materials were thrown out; lava-streams followed. On November 18, 1909, a new vent opened on the island of Tenerife, beginning explosively like all the other new craters, followed by very abundant lava-flows. The action continued for ten days. In modern times several new volcanic islands have appeared in the sea, which will be mentioned in connection with submarine volcanoes.

Submarine Volcanoes

On the bed of the sea there are many more active volcanoes than there are on the continents. Volcanic islands, to which class all oceanic islands belong, are merely submarine volcanoes which have built up their cones above sea-level. Oceanic islands are those which rise abruptly from deep water and are far removed from any large land-mass. The number of active submarine volcanoes is an estimate, since their eruptions can be observed only by unusual good fortune and are seldom visible for any great

distance. It is important to bear in mind the differences in the products of terrestrial, or subaërial, volcanoes, on the one hand and those of submarine vents, on the other, because of the bearing which the distinction often has upon problems of historical geology. It may be said at once that the difference is not great and that it is often exceedingly difficult to determine whether a given volcanic accumulation was made on the land or on the sea-bed, because lava-flows and the pyroclastic materials, scoriæ, pumice, bombs, and ash are ejected from both terrestrial and submarine vents. The following characteristics will assist in making the distinction:

1. Submarine volcanic accumulations are comformably interstratified with sedimentary deposits, the marine origin of which is determinable. This is not entirely decisive, for a land-surface on which are volcanic masses may have been depressed beneath the sea. The strata underneath the volcanic rocks are normally eroded in the case of terrestrial vents, not in that of submarine ones.

2. Submarine lavas are almost always accompanied by tuff, the water favoring the breaking up of the lava.

3. "Pillow-lavas," in which the surface of the flow is lumpy and appears to be covered with cushions, are believed to be characteristically submarine.

4. Contact with water favors the formation of glass, a nonconductor, beneath which the lava flows to greater distances than on land and hence the slopes are gentler.

5. Submarine bombs do not show the effects of rapid revolution while in a plastic state.

6. Tuffs deposited in the sea may, as a rule, be easily identified, but the origin of the ash, terrestrial or submarine, is much more difficult to determine.

Submarine cones are not attacked by the destructive action of the sea until they have been built up nearly to the surface, for wave-action is unimportant below depths of 100 feet. Diastrophic uplift may expose the submarine base upon which a land volcano stands. Ætna, for instance, rises from a base of submarine masses of cemented lapilli of basaltic glass.

New Volcanic Islands

While it is not difficult to identify an island newly arisen above the surface of the sea, it is often impossible to say whether the

volcanic opening itself is new or old. Many new islands have appeared from time to time within the last century, but most of them have had only an ephemeral existence. How many of these were merely old submarine volcanoes that had built themselves up above sea-level, and how many were new openings through the sea-floor, there are seldom means of determining. One case, which almost certainly was a new vent, is that of an island which appeared off the southwest of Sicily in 1831 and which received a great multiplicity of names. According to the rules of geographical nomenclature, the English name, Graham Island, should be used. The new volcano broke out at a point which had been sounded a short time before and depths of 100 fathoms had been determined. The eruption was witnessed by a Sicilian sea-captain from his ship; in the course of a few weeks there was built up a cone of a mile in diameter at sea-level and 200 feet high. When activity ceased, the cone of loose scoriæ and ash was cut down to a shoal by the action of the waves.

Barren Island, which appeared in the Bay of Bengal in 1819, had a history very like that of Graham Island, except that no previous soundings were made on its site.

In the Greek archipelago the group of islands known as Santorin has been the scene of repeated volcanic outbursts for more than 2,000 years. The outer islands are evidently fragments of an ancient ring and within this ring is a cluster of small islands, which appeared above the sea in 186 B.C. and 1573, 1707, and 1866 A.D. respectively.

Of a different type are the Bogoslof Islands which arose north of the Aleutian Islands of Alaska. Old Bogoslof was formed in 1796, the eruptions continuing at intervals, till 1823. New Bogoslof arose in 1883 and, between these, a third and a very large island appeared on May 28, 1906, "giving off clouds of steam and smoke from any number of little craters scattered all over it." (Gilbert.)

Geographical Distribution of Volcanoes

In the most ancient known rocks, those of Archæan time, volcanic action would seem to have been universal, occurring in all large land areas and also, no doubt, in the bed of the sea. In the succeeding Palæozoic era, volcanic outbreaks were greatly reduced in amount and restricted to certain particular regions,

shifting to new regions from time to time. Mesozoic volcanoes had quite a different distribution from those of the Palæozoic and foreshadowed the distribution of the Cenozoic and Recent eras, the latter again marking a great restriction of volcanic areas.

For example, in the Palæozoic and early Mesozoic eras (Triassic period) igneous intrusions and volcanic effusions occurred in the Appalachian and Atlantic border lands, from the Gulf of St. Lawrence to northern Georgia. After the Cretaceous period, North America, north of Mexico, had no volcanoes save in the far West and on the Pacific Coast, extending eastward to Idaho and Wyoming in the north, and New Mexico in the south, while Recent volcanoes are all in the Pacific Coast region, from Alaska southward. Similar shifting of volcanic centers is to be noted in all the other continents.

It is not possible to state, with confidence, the number of volcanoes which are active at the present time, for the dormant vents cannot always be distinguished from the extinct ones, especially as some of the most extensive and important volcanic regions have been known to Europeans for less than four centuries. Several vents that had been supposed to be extinct have broken out again in comparatively modern times. For instance, Santa Maria in Guatemala erupted in 1902 for the first time since the discovery of the country, and the first historic eruption of Vesuvius was in 79 A.D. For such reasons, the number of vents now active can only be estimated.

According to Sapper the number of volcanoes which have erupted within historic times is at least 430, and that of finally extinct vents is many times as great. Of these active vents 275 are in the northern and 155 in the southern hemisphere. Dividing the globe into Pacific and Atlantic hemispheres, of which the former is nearly all water (see p. 7), we find a great preponderance of active vents on the Pacific side, 336 to 94 in the Atlantic hemisphere. Some volcanoes, such as Ætna, are solitary and far from any other; much more commonly they are arranged in groups or bands, which show a definite relation to the tectonic features of the globe.

It is a very striking characteristic of the present distribution of volcanoes that they keep to the neighborhood of the sea and avoid the interior of the continents. Two-thirds of the active

vents are on islands and nearly all of the others follow coast lines and mountain ranges which are themselves near the coasts. However, that nearness to the sea is not indispensable to volcanic activity is shown by the East African vents, five of them arranged on a north-south line which is 200 to 500 miles inland and one is over 800 miles from the Indian Ocean. There is also good reason to believe that volcanic eruptions occurred at Mergen in Manchuria (500 miles inland) at the beginning of the eighteenth century.

This avoidance of the continental interiors was not always to be found in past geological ages. Even in a very late period, the Tertiary, which immediately preceded our own, there were volcanic areas far removed from the sea. The volcanic fields of Utah, Arizona, and New Mexico extended 1,000 miles inland from the Pacific Coast, which was in much the same position as now. In Europe there is a belt of extinct Tertiary volcanoes which runs parallel to the Alps and Carpathians, from central France (Auvergne) and western Germany (the Eifel) to Bohemia and Hungary.

Active volcanoes of the present time are, for the most part, arranged in three principal belts which have a general north-south direction, though pursuing a more or less sinuous course. Two of these belts together encircle the Pacific Ocean; one follows the American coast from Alaska to Cape Horn, but with long interruptions. In the Aleutian Islands and along the coast of southwest Alaska are many active vents, but British Columbia has none. The volcanoes of the United States, the magnificent cones of the Cascade Mountains in Washington, Oregon, and California, are believed to be all but extinct, though Lassen Peak has recently erupted. After a long interval come the many active vents of Mexico and Central America and the South American Andes.

The western Pacific belt is chiefly made of series of islands in long, curved lines, like so many garlands; these islands are parallel to the Asiatic coast, until the East Indian islands, the Philippines, Borneo, etc. are reached and the line continued through the South Pacific archipelagos and New Zealand to the Antarctic Circle. The coincidence of the volcanic and earthquake belts which encircle the Pacific is very close.

The third principal volcanic belt is in the eastern bed of the

Atlantic and the vents are all placed on a ridge which rises very gently from the sea-floor and over which the water is only about 1,000 fathoms deep. While the north-south trend of the belt is obvious, the vents are not arranged in lines, as they so distinctly are in the Pacific, but in groups and clusters. Included in this band are Jan Mayen and Iceland in the far north, then a very long distance in which no vents are known, until the Azores are reached, a group of islands, which are mostly extinct cones, but retain some activity. The Madeira group is extinct, but the Canaries and Cape Verde have active vents. St. Helena, Ascension, and, in the far south (latitude 38° S.), Tristan d'Acunha are islands of volcanic origin, but no longer active. It is a remarkable fact that, except Central America, which is on the Caribbean Sea, the continental coasts of the Atlantic have not a single volcano, either active or that became extinct in late geological times.

In addition to the three principal belts above mentioned there are two other subsidiary bands: (1) the north-south series of volcanoes in East Africa, which seem to be verging toward extinction, and (2) the transverse band, equatorial in direction, of the Central American, West Indian, and Mediterranean volcanoes. The Tertiary volcanoes of Europe form another band parallel to this.

That there is a relation between the volcanic bands and the great tectonic features of the earth is plain; these bands are everywhere parallel or coincident with the coast lines and mountain chains. On the west coast of the Americas, the volcanic cones form the highest peaks of the mountain ranges from which they rise. In Europe, as has been said, the great mountain ranges of the Pyrenees, Alps, Carpathians, etc. have a line of extinct volcanoes parallel on the north and, on the south, the Mediterranean belt of active vents, but the mountain ranges themselves are free from volcanoes. Whatever the reason, the relation of the volcanic bands to tectonic lines is too general to be a coincidence.

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CHAPTER VIII

THERMAL SPRINGS AND GEYSERS — CAUSES OF VOLCANIC AND INTRUSIVE ACTION

Ordinary spring water has a temperature which is nearly or quite the same as the annual average air-temperature of the locality. A thermal spring is one of which the water has a temperature distinctly above that average, and, in different springs, ranges from a slight excess to the boiling point. Thermal springs owe their existence to two quite different classes of agencies: (1) Those which occur in volcanic regions, active or extinct, in which the uncooled masses of subterranean rock or the vapors given off by them cause a high temperature in the waters which traverse them. (2) Those springs which are situated in regions of highly disturbed rocks, folded or fractured, in which water can descend to great depths and yet return to the surface, becoming heated by the ordinary and universal internal heat of the earth. Even the water of deep artesian wells is too warm to drink without refrigeration.

The distribution of this second class of springs, which are by far the most numerous kind, is controlled by the structure of the rocks. A map of the United States, on which the localities of thermal springs are marked, shows that the mountain ranges of folding are accompanied by lines of thermal springs. The Appalachians, in the East, have many such springs, and the successive ranges of the great Western Cordillera, from the Rockies to the Pacific Coast Ranges, have them in greater numbers and of higher temperature. In the intervening Mississippi Valley and Great Plains, where the beds of rock are nearly horizontal and but little disturbed, thermal springs are almost unknown, the only exception being the hot springs of Arkansas, which rise through an island of intensely folded and compressed rocks. There are many springs which are technically thermal because their waters have a slight excess of temperature, but owe this excess to local conditions of vegetable decay, oxidation of pyrite, and the like.

The hot waters of volcanic regions are, by many geologists, believed to be of two different modes of origin: (1) Those which are of surface, or meteoric origin, rain-water, in short, which Suess called *vadose*, and (2) the *juvenile* waters of Suess, which are believed to be of magmatic origin, never having been on the earth's surface before. The actual occurrence of springs which carry exclusively juvenile water has not been proved, but that magmatic waters do flow for long periods of time is exceedingly probable, and if so, they must contribute to the waters of hot springs, even though they should not form such springs of themselves. Spring deposits are described in Chapter XII.

Geysers are periodically erupting hot springs, which may be called "water volcanoes." The eruptions may succeed one another at remarkably exact intervals or their periods may be very irregular. Old Faithful, in Yellowstone Park, is a universally known instance of perfect regularity, erupting at intervals of 65 minutes and throwing a column of water, accompanied by clouds of steam, to a height of 250 feet. In many other geysers the interval is much longer, the volume of water and steam much greater and rising far higher, while others are smaller and less voluminous.

Geysers are rare phenomena, otherwise they would be geological agents of much importance: They occur at present in only three regions of the world, Iceland, New Zealand, and the Yellowstone Park and California in the United States (Allen), all of them areas of volcanic activity, either going on now, as in Iceland and New Zealand, or in the late geological past, as in the American areas. Recent studies of the Yellowstone geysers have shown that for them, at least, the waters are chiefly vadose, with the addition of about 18 per cent of juvenile or magmatic origin. The source of heat is not merely the subterranean masses of uncooled lava which underlie the Park, but the superheated steam and gases which ascend from these lavas.

In Iceland the geysers show a greatly diminished activity since they were first observed. The interval between eruptions of the Grand Geyser, for instance, has increased from thirty minutes in 1772 to twenty days in 1883. The New Zealand geysers were destroyed by the violent outbreak of the volcano Taruvera in 1886, but the Waimanger Geyser resumed operations in 1890, to cease once more in 1904. This was the largest of all geysers, throwing its column to a height of more than 2,500 feet.

As early as 1846 the great German chemist, Bunsen, investigated the geysers of Iceland and reached a satisfactory explanation of them. He first determined that the water was meteoric, and next, that the temperature of the water-column, which he sounded to a depth of 80 feet, decreases from below upwards and in all parts of the column rises continually after an eruption, but, until shortly before the next eruption, the temperature at no level in the column rises to the boiling point for the pressure at that level. It is in the middle of the height of the column that the boiling point is most nearly reached. The lifting and slight overflow of the water relieves the pressure somewhat and instantly a great volume of water, at the hottest level, flashes into steam explosively and throws out the column of water. How long the eruption continues depends upon the water supply and the rapidity of steam generation. Artificial geysers have been successfully made.

The Mechanism of Intrusion and Extrusion

In spite of remarkable progress which has been made of late years there remains much that is mysterious and unexplained in igneous activity and this is because so little of it can be directly observed and, for the most part, the manner of action must be inferred from its effects. Extrusion has been intensively studied at many volcanic vents, but intrusion, in the nature of things, is beyond the reach of observation.

Intrusion takes place at varying depths below the surface though almost always at depths where, owing to rock-pressures, open fissures or cavities cannot exist for any length of time. The magma must therefore make its own way along the lines of least resistance, and the question immediately arises, what is the driving force which enables the magma to overcome such great resistances? Some geologists have regarded the magmas as passive, being merely squeezed by diastrophic compression, as juice is squeezed out of an orange, but the trend of investigation has been to attribute more and more importance to the magmatic vapors and gases and to regard the magma as extremely active. While diastrophic compression is an undoubted agent in forcing magmas into the intruded rocks, the principal driving force near the surface is now believed to be due to the superheated vapors which are under enormous pressures. The cylindrical pipes of the Eifel, of southern Germany, and of South Africa driven through several thousand

feet of overlying strata, like so many gigantic punches through a sheet of tin, are eloquent proofs of the expansive and explosive force of these vapors.

As the more or less fluid magma must follow the lines of least resistance, it breaks through and across the intruded strata in a way that may be remarkably regular or extremely irregular. In different parts of its course, the same plutonic body may be dyke, sill, chonolith, etc., etc. A dyke may terminate upwards in a sill (Fig. 14), or if it breaks through to the surface, in a lava flow; or it may give off sills at various levels of its course. A laccolith may be smoothly bounded by the containing strata, or it may send out many sills and apophyses and thus form one of the curious bodies known as a "cedar tree laccolith" (Fig. 21). The fluidity of the magma is another factor in determining what shape the intruding body shall assume. Under similar conditions of resistance, a very viscous and pasty magma will form laccoliths, while a very fluid one will make sills.

Inasmuch as we cannot postulate deep-seated caverns which the ascending magma may occupy, we have to explain the disposal of the rocks which formerly occupied the place now taken by the intrusive mass. The enormous batholiths, with a cubic content of hundreds or even thousands of miles, have in some fashion taken the place of preëxisting rocks. Sometimes there is no difficulty in seeing how the intrusive has made room for itself, the intruded strata being pushed aside, either by folding or shattering them. Snake Hill, New Jersey, is a large stock, given off from the great Palisades sill, which made its way upward by displacing the Triassic sandstones that it has invaded. Following the contact around the hill, the sandstone beds may be seen in all sorts of attitudes, where they have been pushed aside by the ascending magma. The dyke in Fig. 57 has wedged the walls of country rock apart and, were the dyke removed, the walls would fit together.

Often, however, the disposal of the rock which originally occupied the space now filled by the igneous rock is far from obvious. To meet this difficulty, Professor Daly proposed his hypothesis of "overhead stoping," employing a miner's term for the removal of blocks by the wedging action of the magma. The loosened blocks are then supposed to sink into the magma and be more or less melted and assimilated. The batholith at Marysville, Montana (Fig. 3), would seem to require some such explanation.

This is the problem of assimilation in another form (p. 52) and has the same difficulties to meet. The energy of intrusion is eloquently displayed along the margins of many batholiths, where the country rock is shattered and great blocks are torn off and embedded in the plutonic mass. Such blocks are called *inclusions* or *xenoliths* (from the Greek *xenos*, a stranger) and, on a smaller scale, they occur in other plutonic bodies, such as dykes, sills and laccoliths, and those in the figure (Fig. 25) have sharp edges uncorroded by any solvent action of the magma.

To sum up, the force of intrusion is partly that exerted by the magmatic gases and vapors assisted in varying degrees by diastrophic compression. The problem of the removal of the preexisting rocks, though explicable in individual cases, has not yet found a satisfactory general solution.

Extrusion or *Vulcanism*. More than fifty years ago, the late Professor J. W. Judd concluded from his study of Stromboli that "a volcano is a gigantic steam-engine," and this, with the addition of "other vapors and gases," is very much the opinion held by most students of the subject. Not that a complete and satisfactory explanation of vulcanism has been formulated, but much progress has been made of late.

A theory of vulcanism, to be adequate, must explain (1) the high temperatures involved, (2) the origin of the magmatic gases and vapors, (3) the derivation of the magma, (4) its "ascensive force" (in Dana's phrase), (5) the geographical distribution of volcanoes, and (6) the shifting of the seats of volcanic activity which dies out in one region and appears in another.

(1) The explanation of vulcanism should not be conditioned by any particular theory of cosmogony, yet we must assume the unity of origin of the solar system and that the planets were originally highly heated. In whatever manner the solar system may have originated, there seems no doubt that its members are highly heated internally, save for the satellites that may have lost their original heat because of their small size. So far as the earth is concerned, the high temperature of its interior is hardly open to question and we may conclude that the heat of volcanoes is, for the greater part, at least, primordial and original. Whatever additional heat is required to explain the phenomena, its origin is not so clear, but in some instances, if not in all, additional heat is generated at and near the surface. We have seen that in Hale-

maumau, the lava pool of Kilauea, the surface temperature is more than 100° C. hotter than the lava at a depth of 20 feet. This increment of temperature is due to the gases which are bubbling up through the highly liquefied lava and which react upon one another. It has been suggested that the additional heat is due to radio-activity, but the content of radio-active substances in lavas is not so great as to favor this view.

(2) The second problem of vulcanism is that concerning the origin of the volatile constituents of the magma, chief of which is steam. The situation of the great majority of active volcanoes in, or near, the sea has naturally suggested that magmatic water was derived from the sea. But in former geological periods and exceptionally at present, we find volcanic vents far from the sea. "There seems to be no reason to postulate a meteoric source for the water and gases which figure in volcanic eruptions." (Harker, p. 47.) "The mineralizing substances are not to be regarded as in any sense adventitious or connected with external conditions, but as *an integral part of the rock-magma itself.*" (*Ibid.*, p. 288.) This opinion is very generally held by geologists. On the other hand, Mr. F. A. Perret, who attributes to steam such great importance in the causation of volcanic phenomena, believes that the magma absorbs the steam in rising through water-bearing strata and Dr. T. A. Jaggar regards the steam of highly explosive eruptions as due to ground water.

(3) Magmas are, of course, derived from the interior of the earth, but it is debatable whether volcanoes are merely supplied from limited reservoirs within the crust, or whether they are connected with the continuous, concentric shells of highly heated, but solidified magmatic material beneath the crust. Slight release of pressure would suffice to liquefy the magma, for pressure raises the melting point of rocks. It has been demonstrated in certain instances, as in the South African diamond pipes, that volcanoes are often, probably always, the surface manifestation of plutonic activities, but the question is: Do these plutonic bodies maintain a connection with the subcrustal, potentially fluid magmas? The very small tidal effect of lunar and solar attraction upon volcanic reservoirs would indicate that these reservoirs cannot be very large. The same inference follows from the exhaustion of the reservoirs and consequent extinction of the vents. It will have been observed that almost all the new volcanoes which have broken out in historic times have had but a brief period of activity.

In the case of Kilauea, it appears probable that several distinct pockets, instead of a single reservoir, supply the lava pool of Halemaumau. "Instead of the boiling-flask picture, therefore, we should think rather of a central collecting tube, with many more or less wide-spreading branches below, leading to local chambers in which crystallization is proceeding under different conditions of temperature and pressure. . . . The heterogeneous character of the gases collected, the temperature conditions within the lava basin, the appearance of the crater when free of all its liquid lava and the dynamic conditions within the lava body when present in the crater, all point to many sources rather than a single source, both of gases and of magma." (Day.)

(4) The ascensive force of lavas is chiefly due to the occluded gases and vapors which they hold in solution, but, no doubt, rock pressure and diastrophic compression frequently assist in producing the effect. Explosive violence would seem to be altogether due to the volatile constituents and it has been shown that crystallization may generate very high pressures by excluding the steam and gas from the crystals. (Morey.) The trend of all recent investigation is to show that magmas are not passive liquids, subject to the laws of hydrostatic pressure, but are, on the contrary, extremely active and powerful dynamic agents.

(5) The distribution of volcanoes in narrow linear belts is obviously determined by diastrophic factors. The volcanic belts are plainly related to the mountain ranges, in which, or parallel with which, they are placed. Coast-lines are also determined, for the most part, by the diastrophic agencies and hence the parallelism of the volcanic belts with mountain ranges and coast-lines is because of the dependence of all three upon the same agencies. When the plutonic bodies are solidified through crystallization, the volcanic vents which were supplied from that reservoir must cease their activity.

No active volcano of the present day is of great geological antiquity; with the possible exception of some of the Andean vents, no volcano now active is believed to have come into existence before the Miocene epoch of the Tertiary period, and many, if not most, of the modern vents are of still later date.

Vesuvius and Kilauea differ so profoundly in the phenomena of their activity that it is, at first sight, difficult to believe that the same agencies are at work in both. Yet the independent study

of the mechanics of eruption leads to the same conclusion, and it is instructive to compare the results reached by Drs. Day and Perret.

Day	Perret
"Through all of these studies one conclusion seems to stand fast whenever it is applied, namely that the outstanding factor in determining the character of modern volcanism is the gas content of the crystallizing magma. If this be mainly of steam released in a closed chamber, as at Lassen Peak, then only steam explosions are to be expected as the surface manifestation of the crystallization of the magma below; if to the steam are added such chemically active gases as chlorine, sulphur, hydrogen, and the hydrocarbons, then chemical reaction between these will be a sufficient cause of the higher temperatures and lava-flows of the character well known at Vesuvius, Stromboli or Kilauea." *Op. cit.*	The following facts seem to be proved by observation. "(1) The filling of the crater with magma from the depths is a slow process. (2) There results an accumulation of liquid material within and beneath the volcanic edifice, with gradually increasing gas-content and tension. (3) The release and discharge of all or part of this accumulation constitute eruption and with consequent exhaustion give to the cycle of manifestation its quality of periodicity. (4) The eruptive element, par excellence, is gas. (5) The main function of the magmatic reservoir is the evolution and accumulation of gas. (6) The actual upward movement of magma from its reservoir is too slow to permit of its being the actual carrier of all the gas which is emitted, whence we may deduce: The magma is a paste which permits the transfusion of gas and which changes into liquid lava in the upper part of the column." *Op. cit.*

The harmony of the results attained by two entirely independent observers is very striking and is strongly indicative of their truth. Essentially, these results are a reaffirmation, with important additions, of Judd's thesis propounded 50 years ago.

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(Other references the same as for Chapter VII.)

CHAPTER IX

DIASTROPHISM — EARTHQUAKES

The history of the earth's crust, as that is recorded in the rocks, makes it certain that there have been great changes in the arrangement and extent of land and sea and in the altitude of the land-masses. Almost all of the continents have, at one time or another, been submerged beneath shallow, *epicontinental* or *epeiric*, seas and large areas of the present shoal-water seas were once land surfaces, such as Hudson Bay, the Gulf of Maine, the North Sea. These diastrophic movements have continued to the present time, but there is much difference of opinion concerning the facts, which have been affirmed and denied in bewildering fashion, often in the interests of certain theories. Diastrophic movements of the present time that can be detected are entirely of the *epeirogenetic* (see p. 5) class, for the orogenic or mountain-making processes are not open to observation, even though they may still be at work, because they are so slow and deep-seated.

Diastrophic movements may be in any direction, upward, downward or horizontal, and may be either direct, vertical uplift or depression, warping or curving upward or downward, or tilting and inclining. Furthermore, they may be distinguished as secular, extremely slow and gradual, or rapid and sudden. The former are principally warping and tilting, the latter vertical uplift, or depression, and these are almost always associated with earthquakes, in connection with which they will be considered. It might seem more logical to discuss all classes of modern diastrophic phenomena together, but, as it is not improbable that the secular and the sudden movements were brought about by quite different agencies, it is better to keep them apart. Though elevation and depression affect the interior and the coasts of land-masses in the same way, it is, for the most part, impossible to detect interior changes, save by means of repeated, precise surveys, and these have seldom been made in proper form. On the coast, the sea

affords a means of detecting even minute changes. But the problem is immediately suggested: Are these changes in the land, or in the sea? Along open coasts, changes cannot be local, they must be general. Professor Daly has found evidence in widely separated regions of a comparatively modern rise in the general sea-level of about sixty feet. This rise he attributes to the melting of the immense ice-caps which, in the Pleistocene, buried such vast areas of the continents, but this has nothing to do with diastrophism. Coasts which are locally raised, or depressed, or where opposite movements are near together, prove that the change was in the land. Formerly, it was customary to speak of "elevation and depression" of the land, but since Suess denied the possibility of an upheaval, except by volcanic agencies, the terms, "positive and negative displacements of the strand-line," have been widely used as non-committal. But these terms are not neutral, for they refer to the sea; a "positive displacement" means a rise of the sea, or a sinking of the land, and "negative displacement" means a rise of the land or fall of the sea. The older terms are here employed.

In estimating the effects of diastrophic movements along the sea-coasts, it is necessary to guard against being misled by changes, often very striking, which have been brought about in an entirely different manner. Many shores, like the east coast of England, are being cut back by the waves, sometimes with appalling rapidity, bringing quite deep water over the sites of farms and villages. On the other hand, the land is, in many places, advancing at the expense of the sea, the coasts extending outward by deposition of sand and mud. Around the head of the Adriatic Sea, the land has grown several miles in the last 2,000 years; Ravenna, which was a Roman naval station and seaport, is now 20 miles inland. In such retreats and advances of the sea, diastrophism is not involved.

An examination of the various coasts of all the continents (except Antarctica, of which nothing is known in this respect) reveals the fact that long stretches of these coasts are now, or have lately been, moving upward or downward. On the whole, elevation predominates and has done so through the earth's history, though with long periods of depression. The vital importance of diastrophic upheaval is made plain by the fact that it is the only general counteracting agent to the ceaseless attack of the waves and

currents on the coast, which they cut back like a horizontal saw. Were it not for diastrophic elevation, all the continents and islands would long ago have been swallowed up by the "all devouring sea."

The evidence by which diastrophic movements may be proved differs in accordance with the direction of the movement. Land which has been raised from under the sea shows unmistakable signs of marine action in erosion, or deposition, or both, while land upon which the sea has encroached is covered up by the water, and, in most instances, the evidence of its movement is indirect. Sometimes, as in the case of the Gulf of Maine and the North Sea, the bottom may be mapped by soundings and made to reveal its terrestrial character. This method has not, as yet, been applied in many instances.

The shores of the Mediterranean and its islands have been the seat of an immemorial civilization, and many ancient buildings, more or less ruinous, remain to testify of diastrophic movements upward, downward, or both. These ruins have been the subject of long and frequent controversy, not only as to the explanation of the facts, but also as to the facts themselves. Many erroneous observations and inferences have been made which subsequently were perforce abandoned. A very celebrated and much-debated example of oscillations of level is the so-called Serapæum, or the Temple of Jupiter Serapis, at Pozzuoli on the Bay of Baiæ, near Naples. This building, which was perhaps a market, or public bath, has three monolithic columns of marble, some 40 feet high, which have remained upright and have registered the changes of level for nearly 2,000 years past. This building and its surroundings were selected by Sir Charles Lyell as a particularly favorable example of oscillations of level, because three quite independent lines of evidence, archæological, documentary, and geological, concur in the same conclusion.

The archæological evidence is chiefly afforded by the building itself and especially by the three monolithic columns. Whatever its nature and purpose, the "Serapæum" was originally erected on the land, not, like several Roman villas in the adjacent bay, in the water, and its date is probably the second or third century A.D. While still in use, the building had begun to sink and was invaded by sea-water, for a second floor was laid on a fill about eighteen inches deep above the original pavement and, on this new floor, false bases were put around the foot of the columns. At an un-

known date, a shower of volcanic ash filled the court to a depth of twelve feet and when the continued sinking brought the water to a height of twenty feet above the second floor, the lower part of the columns was protected by this ash against the attack of the boring mollusc, *Lithodomus*, which still abounds in the waters of the bay. The portion of the columns which was submerged and

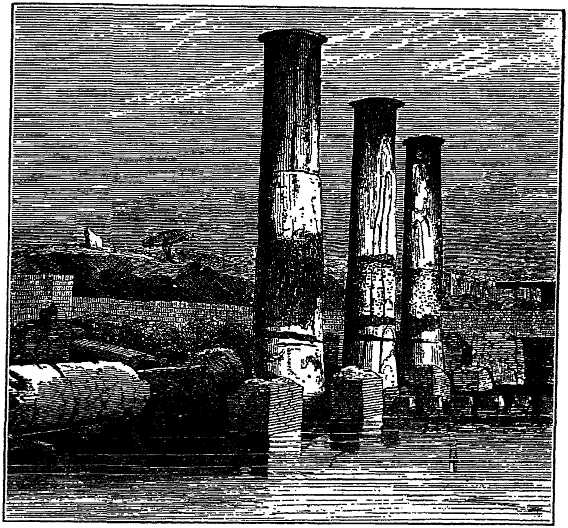

FIG. 58. — Monolithic columns of the "Serapæum" at Pozzuoli, Italy, in 1836. (After Lyell, courtesy of Messrs. John Murray, London)

unprotected was honeycombed by the borer and now each column has a belt, nine feet wide, which is rough, full of tunnels made by *Lithodomus* and in sharp contrast to the smooth portions above and below and exactly of the same width and level on each pillar, obviously a water-level. When first excavated, many of the tunnels still contained the shells of the boring molluscs which made them, but these were long ago carried away by souvenir-hunters.

Taken together, the double floor and the columns show that

a downward movement began in Roman times, that a shower of volcanic ash filled the structure to a depth of twelve feet and that depression continued until the maximum depth of twenty-one feet was attained. At that level there was a long pause, allowing time enough for the boring molluscs to fairly riddle the marble over the nine-foot belts which were exposed to them. When the upward movement began is not known, but it continued until the original floor was above sea-level, when the columns were discovered and excavated in 1741. At the end of the eighteenth, or beginning of the nineteenth century, a renewed depression began and Sir Charles Lyell's drawing, made in 1836, shows the upper floor covered with water, and the downward movement is still in progress.

The documentary evidence is contained, first in the Latin accounts of the region which shows that the plain on which the "Serapæum" stands was land; second, the Mediæval itineraries make it plain that in the Middle Ages, the sea came to the foot of the bluff, on which stands a ruin, identified as one of Cicero's villas; third, that the reëlevation had begun to attract attention before the end of the fifteenth century, for there is extant a grant of land at Pozzuoli "where the sea is now drying up," issued in 1498 by Ferdinand and Isabella of Spain. The final upheaval is supposed to have occurred in 1538, when the new volcano, Monte Nuovo, broke out in the neighboring Phlegræan fields, but this is only inferred.

The geological proof is, first, that at some not distant period, the sea came up to the foot of the low cliff, as is shown by the sea-caves, cut by the waves in the soft volcanic tuff and other marks of wave-action. Second, the plain, called *la Starza*, which extends back of the "Serapæum" has a surface made up of marine deposits filled with shells and remains of other sea animals, exactly the same as still live in the waters of the bay. Beneath these marine deposits is an old soil, from which many small objects of Roman make, coins, bronzes, pottery, etc., have been taken. This evidence shows that a small plain, cultivated land in Roman times, was depressed beneath the sea and, after remaining at that level for some time, was again reëlevated.

It has been attempted to show that these unquestionable changes of level around the Bay of Baiæ are not properly diastrophic at all, but volcanic. This contention lends special interest to the

studies of R. T. Günther, made in 1903, which cover not only the whole Bay of Naples, but extend down the Italian coast to Pæstum and northeasterly to Rome. At the time of the Greek settlements, the coast stood at least 6 meters (20 feet) above its present level and depression began in the time of the Roman Empire, increasing in the Middle Ages, until the coast was 20 feet or more below its *present* level, making a total downward movement of 40 feet or more since the fifth century B.C. At the close of the

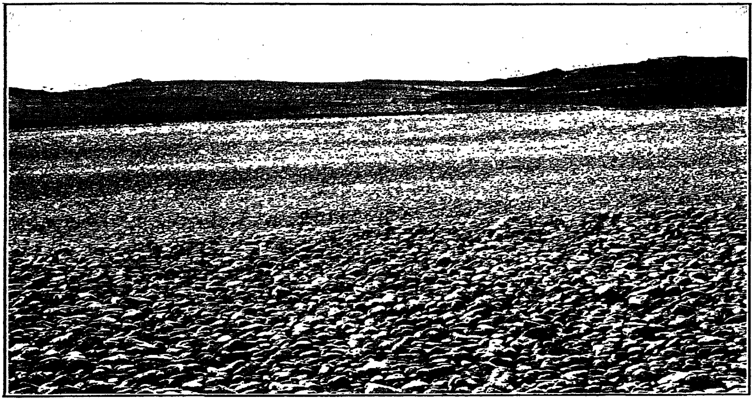

FIG. 59. — The 100-foot raised beach near Brein Phort, Argyll, Scotland. (Geol. Surv. Gt. Brit.)

fifteenth century, reëlevation had gone so far as to awaken attention, yet it did not proceed sufficiently to lay bare all of the submerged Roman territory. The second downward movement, which followed, is still going on. (Supan, p. 465.)

Evidences of Elevation. Ancient buildings, as indicative of oscillations, were considered in the foregoing paragraphs; in other instances, such buildings show only upheaval and it will suffice to cite one very remarkable case discovered by Fraas on the East African coast. At Mombasa there was an old Portuguese defensive work of stone, which was destroyed in 1696. To the stones of the ruin, which are now from 13 to 16 feet above tide,

are attached enormous numbers of oyster shells, still fixed to the spots where they lived. This is a rise of 16 feet in 212 years, a movement quite unnoticed by the inhabitants of that coast.

One of the best proofs of elevation is the raised strand-line, commonly called a raised beach. The former term is better because a beach is made of loose materials which may speedily be removed by erosion, leaving only a terrace, or step, cut in the rock, which is a strand-line, with or without the beach. These raised strand-lines are found on very many coasts in all parts of the world and in all sorts of climates. When preserved, the beach is made up of shingle, gravel, or sand, usually of both pebbles and sand in varying proportions, and it contains, in greater or less abundance, the shells and tests of marine animals. Often, in beaches lately raised, seaweed and barnacles still remain clinging to the rocks. Raised strand-lines, usually with beaches, are especially frequent in high northern latitudes, along the coasts of lands which were covered with the immense ice-caps of the Pleistocene.

The Scandinavian peninsula is the area where secular elevation was first observed. This was in the eighteenth century and the coast has been carefully observed and repeatedly surveyed ever since. No part of the world has been more hotly debated than Scandinavia, but now the facts may be taken as well established and very probable inferences may be drawn from them. Strand-lines are found up to an altitude of 1,000 feet and the principal axis of movement is along the line of mountains which form the watershed between Norway and Sweden. Elevation increases northward and at the North Cape there is a series of marine terraces, with shells of the same species as now live in the Arctic Sea. The movement is not a simple uplift, but an *upwarp*, forming a very flat dome. The raised strand-lines, which were originally horizontal, are no longer so, but slope downward toward the sea and, at the same time, the peninsula was tilted, rising northward and, south of Stockholm, going down, as was demonstrated especially by the surveys of Baron de Geer.

On the west side of Norway is a coastal plain, some twenty-five miles wide, which is a "plain of marine denudation," cut by the waves in solid rock and now raised a little above the sea. This is an interesting contrast to the wide coastal plain of the eastern United States, which borders the continent from New York to

Texas. The American plain is also the upheaved bottom of a shallow sea, but is covered to great depths by marine deposits of mostly unconsolidated material. The diastrophic movement of Norway ceased in prehistoric times, in the Bronze Age of human culture, but on the coast of Sweden the movement still continues. The east coast of Scotland likewise displays a series of marine

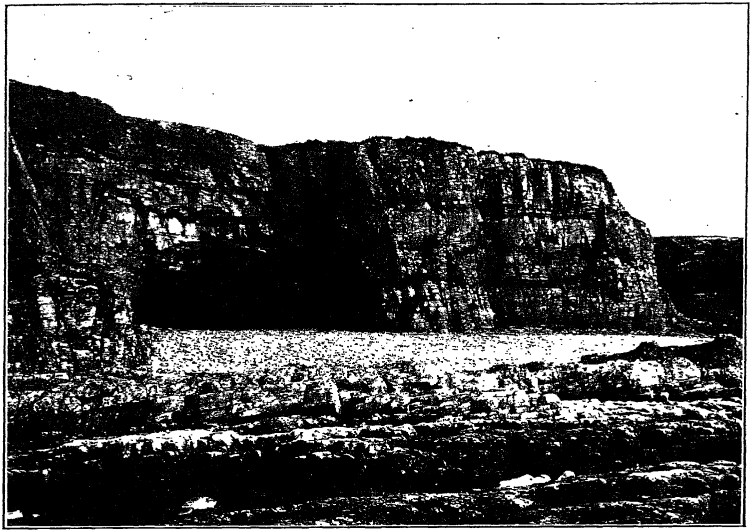

FIG. 60. — Ancient sea cave at edge of 25-foot raised beach, near Brein Phort. (Geol. Surv. Gt. Brit.)

terraces, the highest of which is 200 feet above the sea; wave-cut terraces and sea caves and beaches of coarse shingle are in perfect preservation, as though but lately abandoned by the sea.

On the American coast the raised strands are much the same. South of latitude 40° N. they cease, but increase in altitude northward, from 200 feet at Boston to 700 feet on the eastern shore of Hudson Bay and reappearing on the east coast of Greenland. Indeed, strand-lines, now raised, are cut into almost all Arctic

and sub-Arctic rocky coasts. Baron de Geer found Swedish conditions so accurately reproduced in Canada that he could apply his own methods of measurement and survey.

The Pacific coasts of both North and South America show many raised strand-lines and give abundant evidence of relatively late movements in both directions. Most of these, especially in Alaska, California, and Chile, are associated with earthquakes and will be considered in connection with them. Diastrophic movements are, by no means, confined to high latitudes; raised

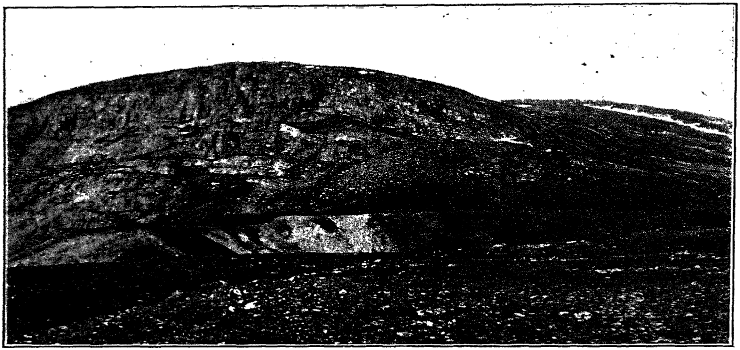

FIG. 61. — Raised beaches on Ungava coast of Hudson Bay. (Geol. Surv., Canada)

beaches occur in all parts of the world and are found on the coasts of all the continents. They are common in the great archipelagos of the West and East Indies; for example, marine terraces are conspicuous on the eastern end of Cuba to one sailing through the Windward Passage. Timor, in the East Indies, is fringed with living coral reefs and raised beaches are to be seen, one above another, to heights of several hundred feet.

Most remarkable of all, perhaps, is Palmarola, one of the Italian islands (Ponza group) in the Adriatic, which from the time of Scrope's map in 1822 rose 213 feet up to 1892, or nearly at the rate of a meter per year. So rapid a rate suggests the sudden movements associated with earthquakes, but these, if they occurred, have not been recorded.

Oscillations of level cannot often be observed in the interior except in connection with earthquakes (*q. v.*), for there is no datum level, such as is afforded by the sea. There are, however, certain lake-beaches, which show that the interior of the continents is subject to diastrophic changes like those of the sea-coast. In Utah there are the remarkably preserved beaches, spits, bars, deltas, etc., of the immense Pleistocene, fresh-water Lake Bonneville, of which Great Salt Lake is the much shrunken remnant. When made, these beaches were, of course, horizontal, but they are no longer so, having been upwarped into a flat dome so gently

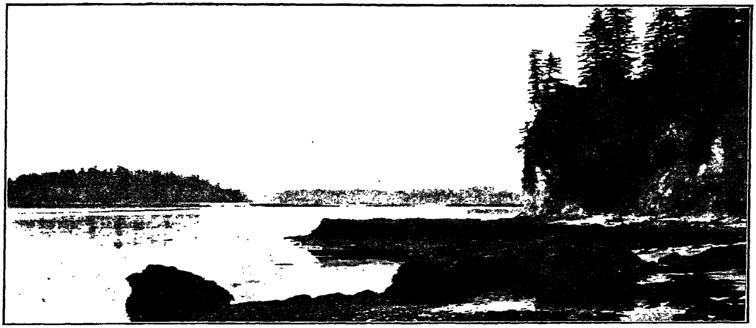

FIG. 62. — Raised marine bench in limestone, Kuiu Island, southeast Alaska. (Photograph by Buddington, U. S. G. S.)

that the rise must be determined instrumentally; there is reason to believe that this upwarp is still in progress.

The Great Lakes have had a very complicated story, beginning when the ice-cap acted as a dam, blocking the natural flow of the water northward. Many beaches remain at various altitudes, marking the height of the water levels. When the ice had melted and the five lakes had withdrawn, each into its proper basin, their connections and outlets were quite different from the present arrangement. Then there was an upwarp, the ground rising to the northeast, as is shown by the old beaches, which are no longer horizontal.

Evidences of Depression. Ancient buildings may indicate depression as well as elevation. At Pozzuoli, the remains of

Agrippa's mole still retain several of the bronze mooring-rings, to which the ships were tied up. At present, these rings are entirely beneath the water, a position in which assuredly they were not originally set. On the north shore of Egypt, several ancient tombs cut in the rock may now be seen entirely submerged.

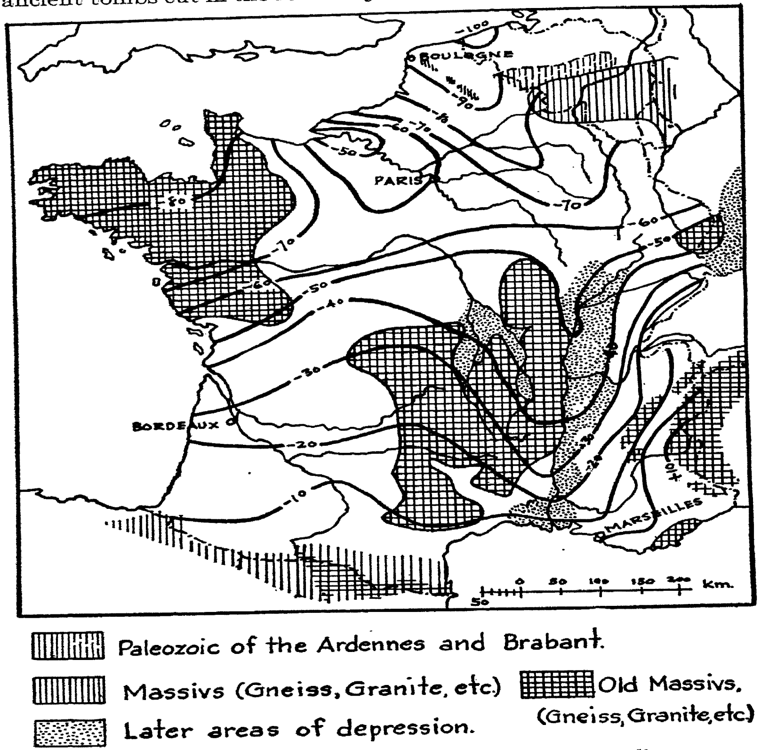

FIG. 63. — Map of France, showing recent subsidence; heavy lines connect points of equal depression. (Kayser)

It is certain that when these tombs were cut, the rock was above sea-level. South of Stockholm, the movement of the Swedish coast is downward. In this area, an ancient hut was discovered, buried under sixty-five feet of Recent marine deposits, which contain shells of the same species as are now living in the Baltic Sea. An unusual opportunity to detect diastrophic movements which are still in progress is afforded by the precision leveling carried out over France in the years 1884–93, after an interval of 30 years following a similar survey. The map, on which lines of equal depression are indicated by contours, shows that all France, except at the foot of the Pyrenees and Alps, where there is a slight rise, is sinking at a remarkable rate. The rate increases northward and reaches its maximum on the coast of the Channel and the North Sea, where depression amounts to ten feet per century. The lines have a general east-west direction and their course is little affected by a change in the character of the rocks, but tectonic features have a profound effect. In the southeast, between the Alps and the Central Plateau, the lines are strongly recurved southward, caused by the Rhone-Saône "Graben," or trench-fault.

The line of 60 cm. (2 feet) depression crosses France with very little deflection, but that of 70 cm. pursues a very irregular course. Between the Palæozoic of the Ardennes and of Brabant and the Seine is another series of recurvatures, of which the axis is from northwest to southeast, determined by one of the principal lines of fracture of the Variscian foldings and is a great area of depression. The middle line of the horst at Boulogne is in this axis. At the mouth of the Seine is an ellipse of diminished sinking, conditioned by the fault which runs 100 km. southeast from Dieppe. (Kayser.)

Much reliance has been placed upon buried forests found below sea-level as a proof of depression, as, indeed, they are, if certainly in the places where they grew, for only the tropical mangrove trees will grow in salt water. On the other hand, stumps may be drifted, until they become water-logged and sink, settling down upon their roots and simulating trees standing where they grew. Such a case is afforded by the "forest bed" in the marine Pliocene of the east coast of England. Long believed to be an old land-surface, it proves to be merely a mass of drifted stumps. If the roots of the stumps can be traced down into the underlying soil, then the forest is a real one and, if below sea-level, is a proof of

depression. Submerged forests are found on the coast of Germany both on the North and the Baltic Sea and also on the coast of Holland, which is believed to be sinking.

Drowned river-valleys are a proof of depression, though one which has been much disputed and denied. A river which flows into the sea cannot excavate its channel below sea-level, and when a submarine channel extends seaward from the mouth of a river, it is very strong evidence of submergence, especially if the continental part of the river valley shows signs of "drowning." The Hudson is an excellent example of a drowned river valley. Looking north from West Point, the manner in which the mountains plunge down into the river is immediately suggestive of a depression which is borne out by the many borings and tunnels, which have been driven through the bed of the river, both vertically and horizontally. The river cut a rocky cañon, the bottom of which is now many hundred feet below sea-level and is continued outward past Sandy Hook, as a submarine trench for 125 miles southeastward. When that cañon was cut, the continent stood 2,000 feet higher and extended at least 100 miles eastward, to the edge of the continental shelf. When depression began, the river's current was much diminished in velocity, deposition taking the place of erosion and the lower part of the river's course being a tidal estuary. At present the ancient rocky gorge (see Fig. 117) is filled with mud, at West Point to a depth of 400 feet, increasing to 700 feet at New York.

Chesapeake Bay is the drowned lower valley of the Susquehanna and the streams which now enter it separately were formerly branches of the river, such as the Potomac and the James and many smaller streams. San Francisco Bay is an obliterated river which, formed by the junction of the Sacramento and San Joaquin, cut through the Coast Ranges and entered the Pacific by the Golden Gate. The ancient delta of this completely drowned stream is revealed by soundings outside of the Golden Gate. Many other submarine extensions of rivers, such as the St. Lawrence and the Congo, have been discovered and, so far as they are true, river-cut trenches, they prove depression.

Sometimes, an ancient and now submerged land-surface may be revealed by the careful study of numerous and accurate soundings. The Gulf of Maine, which is approximately demarcated by a line drawn from the tip of Cape Cod to the southwest point

of Nova Scotia, covers, as has lately been shown by Professor D. W. Johnson, an ancient land surface. In similar fashion, it has been learned that the Irish Sea and the North Sea are submerged lands, typical epicontinental seas. This is confirmed by many other lines of evidence which show that the separation of Great Britain from the continent took place in the Recent geological epoch. When the primitive men of the Palæolithic or Older Stone Age first invaded Britain, they did so dry-shod.

Finally, the character and topography of land recently invaded by the sea are quite different from that which has lately emerged. Coastal lands have, in many instances, oscillated upward and downward, but it is the latest movement which usually determines the character of the area involved, provided that there has been time enough to fix this character. The coast of Maine, with its many rocky islands, has evidently a land topography partially submerged by the sea, which has filled the valleys and lowlands, leaving the higher ridges and hills to stand as promontories and islands. That the latest movement of this coast, perhaps still in progress, is upward, does not affect its character as a coast of submergence.

The Causes of Diastrophism are very obscure, because not susceptible of direct observation, and are therefore subject to much difference of opinion. It is not at all certain that the gradual and the sudden manifestations of diastrophism are due to the same agency, even though it is not always possible to distinguish their effects. The gradual movements are, typically at least, warps, upward or downward, while the sudden movements tend to be vertical.

The late and, in some instances, still continuing rise of land in the high northern latitudes of both hemispheres is very generally regarded as isostatic in nature. These regions were formerly under a gigantic load of glacial ice, beneath which they sank, and since that ice disappeared, they have been rising, though in many areas, Norway for example, the movement seems to have reached its end. No doubt this is, at least, a part of the truth, but isostasy does not satisfactorily account for all the phenomena, such as the movement of adjacent areas in opposite directions. Högboom and others believe that all of the slow diastrophic movements are isostatic in character. (Högboom.) Others, especially the German geologists, attribute diastrophism to the dynamic forces of magmas.

It was formerly believed by almost all geologists that the contraction of the earth's crust from cooling had been the active force of all diastrophic movements, but this had been generally abandoned as inadequate. However, as will subsequently be shown, the contraction hypothesis may yet prove to be the best explanation. Furthermore, the discovery of radio-activity has made it questionable that the earth is losing heat. Mountain ranges and other belts of folded rocks have demonstrably undergone contraction, but it does not follow from this that the earth, as a whole, has shrunk. It seems assured that all forms of subterranean activity, plutonism, vulcanism, diastrophism and earthquakes, are in some manner produced by the heat of the earth's interior, but just how the high temperature operates has not been explained.

Earthquakes

An earthquake is a sudden, more or less violent, disturbance of the earth's surface caused by a shock in the interior. By no means all earthquakes are perceptible to the senses; to demonstrate these *microseisms*, delicate recording instruments, called *seismographs*, are required. Earthquake observatories, which are now widely scattered over the world, and keep a record of all detectible shocks, prove that the number of these is surprisingly great. Seismographs, which record the earthquake waves, as they emerge at the observatory, are of several different types, but they are mostly pendulums, horizontal, vertical, or inverted, provided with a magnifying lever and stylus, which records the earth movements on a revolving drum of smoked or otherwise sensitized paper. A chronograph records the time on the same drum, so that the times of arrival of the different kinds of earth-waves are precisely determined.

The central seismological station of Germany, at Jena, receives reports of 8,000 to 10,000 earthquakes annually, of which some 5,000 are perceptible to the senses, the others appear only in the seismograms. These numbers amount to an average of one earthquake per hour, but they represent but a fraction of all quakes; the earth's crust would seem to be in a constant state of tremor, now here, now there, very much more frequently in some regions than in others.

The *seismograms*, or self-made earthquake records (Fig. 64),

yield much important information, both as to the nature and origin of earthquakes and as to the internal constitution of the earth (p. 2). The waves are elastic, like the waves of sound, and composite in character, but the record permits an analysis of the waves into their components. When the instrument, in a state of rest, is affected by a distant shock, it shows the first preliminary tremors (P, Fig. 64), which, in the record made at Strassburg of the San Francisco earthquake of 1906, lasted for nearly eleven minutes; then the second preliminary tremors (S), which in that particular record continued for almost sixteen minutes.

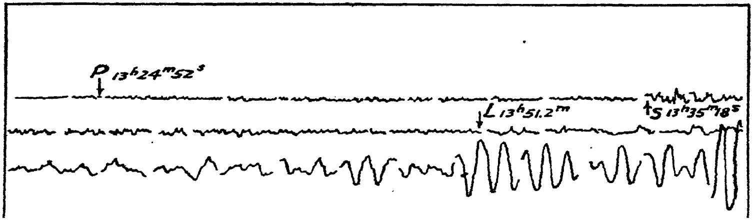

FIG. 64. — Record of the San Francisco earthquake of April 19, 1906, made at Strassburg, Germany. *P*, first preliminary tremors; *S*, second preliminary tremors; *L*, long waves. The continuous line is cut into three segments.

The P waves are interpreted as the longitudinal waves and the S as the transverse waves, which accompany the longitudinal in a solid but not in a liquid medium. The preliminary waves pass through the body of the earth at a high rate of speed in solid rock, much diminished when they enter the loose and inelastic soil. The farther away the point of origin, the deeper the path of the waves.

"It was found by A. Mohorovičić [in] the records of the earthquake of 1909, October 8, in the Kulpa Valley, Croatia, that two distinct compressional and two distortional pulses were present. One pair of these was found to behave at distances of the order of 1000 km. or more, like the P and S known to previous investigators. The other pair traveled more slowly, but appeared to have started earlier." These were denoted by P_g and S_g. "At stations near the epicentre only P_g and S_g were observed. At greater distances P and S arrived before them, so that four distinct

pulses could be traced. At still greater distances P_g and S_g could no longer be recognized but P and S could. The interpretation placed on these facts . . . was that the focus of the earthquake was in an upper layer of the crust and that P_g and S_g were waves that had traveled in this layer directly from the focus to the observing station, while P and S had been refracted downward into a layer where the velocities of propagation were greater and afterwards refracted up again."

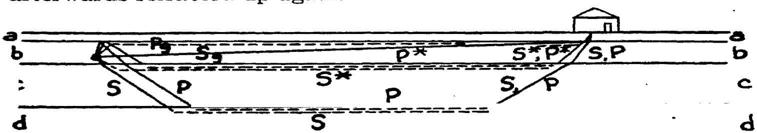

FIG. 65. — Diagram of the probable paths of the six pulses observed in near earthquakes; vertical scale much exaggerated. *aa*, sedimentary layer; *bb*, granite layer; *cc*, intermediate layer (basalt or dolerite); *dd*, lower layer (dunite, etc.). (H. Jeffreys)

"V. Conrad, in discussing the earthquake of 1923, Nov. 28, in the Tauern region of Austria, found the same four waves and in addition a fifth, which he called P*, with a velocity of transmission between those of P and P_g. He suggested that this might be a compressional wave transmitted in an intermediate layer. . . . The existence of the wave P* was confirmed [by Jeffreys] by finding it in the records of the Jersey and Hereford earthquakes of 1926, July 30, and 1926, August 14. The corresponding distortional wave S* was also identified. So long as the epicentral distance does not exceed about 800 km. all these six pulses seem to travel with uniform velocity." (Jeffreys, H.)

Following the preliminary tremors is the main shock, the waves of which (L) are marked by much wider swings of the pendulum and are therefore called "the long waves." The long waves are interpreted as having followed around the crust of the earth near the surface and, by noting the difference in time of arrival of the preliminary tremors and the long waves, it is possible to calculate the distance of the place of origin from the recording instrument. Somewhat later, a second set of long waves may be recorded; these have passed around the earth in the opposite direction from the first set, and, following a longer path, arrive later. In very violent earthquakes the long waves may make the entire circuit

of the earth more than once. Repetitions of the three classes of waves by renewed shocks, with the addition of reflected and refracted waves, from the different shells of the earth's crust (p. 4) often make a seismogram so complicated as to be nearly unintelligible.

In solid rocks the elastic waves of an earthquake are frequently imperceptible, and therefore in mines shocks may not be felt, which, at the surface overhead, may be of destructive violence. For example, the Grand Banks earthquake of November 18, 1929, which was so destructive to the submarine cables, had sufficient energy at Sydney, N. S., to overthrow many chimneys, but was not felt and did no damage in the coal mines at that place.

Nearly all violent earthquakes are followed by *after shocks*, which may continue for weeks, or even months, and sometimes are very energetic, but they do not equal the original shock. They gradually diminish in violence and die away as the dislocated blocks of the earth's crust reach a state of equilibrium.

As the seismographs register the time of arrival of the various classes of waves, *isoseismal* (or *co-seismal*) curves may be constructed by connecting those points on the map at which the shock arrived simultaneously; the curves form more or less irregular ovals, or even circles, the center of which is called the *epicentrum* (or *epicenter*), the point on the surface directly above the place of origin, or *focus*. The irregularities of the isoseismal curves are due to the lack of homogeneity in the rocks near the surface. In well-recorded earthquakes, analysis of the seismograms makes it possible to determine the depth of the focus, which is not a point, but a surface, or even a block. In no case has the depth of focus been found to exceed twenty-five miles and the average is about twelve miles in the cases in which the depth has been determined.

The Phenomena of Earthquakes vary greatly in different places, according to the violence of the quake, the character of the rocks, depth of soil, etc. Violent earthquakes are among the severest scourges of mankind and in a few moments may destroy great cities, with terrible loss of life. In recent years there have been three great earthquakes, in each of which the loss of life has exceeded 100,000: Messina, in the island of Sicily, in 1908 (100,000 +); Tokyo, in Japan, in 1923 (142,000 +); and Kansu, China, in 1923. The latter is very incompletely known and the estimates vary

from one to two hundred thousand. Such terrible destruction of human beings occurs, it will be observed, only in cities and is due principally to wrecked and falling buildings. In the open country the phenomena are displayed in a less complicated way.

A great earthquake usually begins suddenly and with little or no warning. A rumbling sound, increasing to a loud roar, accompanies, or slightly precedes the movement of the ground, which is first a trembling, then a shaking, and finally a rapid swaying, wriggling motion, in which it is often impossible to keep one's feet and many people are attacked with nausea. Frequently the ground has been observed to rise into low, very swiftly running waves, with cracks opening on the crests, closing again in the troughs. If the waves pass under a forest, the trees sway violently, like a wheat field waving in the wind. In all of the very violent earthquakes, fissures open in the ground, which sometimes remain open permanently, which may show a linear, curved, zigzag, or radiating arrangement. More frequently, the fissures close.

In the years 1811 and 1812 the Mississippi Valley was often shaken by violent earthquakes, and had the region been as thickly peopled as it is at present, there would certainly have been great loss of life. Fissuring of the ground was so common an accompaniment of the shocks that the widely scattered inhabitants cut down many trees in the hope that the trunks might serve as bridges over the fissures. It is frequently characteristic of great earthquakes that sand and water are forced up from below in immense quantities, forming little sand-craters, called *craterlets,* which are water-filled funnels.

The "Great Indian Earthquake" of 1897 was one of the most carefully studied of the major disturbances and is thus summed up in the official report upon that catastrophe: "On the afternoon of June 12, 1897, there burst upon the western portion of Assam [in northeastern India] an earthquake which, for violence and extent, has not been surpassed by any of which we have historic record. Lasting about two and one-half minutes, it had not ceased at Shillong before an area of 150,000 square miles had been laid in ruins, all means of communication interrupted, the hills rent and cast down in landslips, and the plains fissured and riddled with vents, from which sand and water poured out in most astonishing quantities; and ten minutes had not elapsed from the time when Shillong was laid in ruins before about one and three-quarters

million square miles had felt a shock, which was everywhere recognized as one quite out of the common." (R. D. Oldham.)

Submarine Earthquakes. Many, perhaps most, earthquakes originate in the bed of the sea; the elastic waves do not spread very far in water, and ships which encounter the shock almost invariably give the same account of it, that they seem to have struck a rock, or run aground, but rarely is any damage done. Reports from vessels that have felt the shock frequently show a linear arrangement on the chart. When any considerable area of the sea-bottom is suddenly raised or lowered, a gravity wave is generated, similar in principle to the spreading circles seen on the surface of a pond when a stone is thrown into it. Though seldom visible in the open sea, the *great sea wave* (often improperly called *tidal wave*) piles up into a gigantic breaker on the coast and often causes more destruction of life and property than the earthquake itself.

Volcanic explosions in the sea-bed, whether or not accompanied by earthquakes, are especially potent in generating these waves. The eruption of Krakatau in 1883 (see p. 108) produced a great wave that devastated the coasts of Java and Sumatra, drowning 36,000 people. In the Peruvian earthquake of 1868, the great sea wave carried the U. S. gunboat *Wateree,* which was at anchor off Arica, three miles inland and left it stranded there. This wave crossed the Pacific in twenty-four hours and broke on the coast of Japan. The Grand Banks earthquake of November 18, 1929, produced a wave which did great damage on the south shore of Newfoundland, which "consists of a series of peninsulas separated by long narrow inlets of the sea, all of them with steep and rock-bound shores. Up these inlets the tidal waves rushed, concentrating and piling up to heights as great as fifty feet above sea-level." (Keith.)

Distribution of Earthquakes. A map on which earthquakes are indicated by shading, so that the depth of tint would indicate the frequency and violence of the shocks, shows that earthquakes are arranged in a definite manner with regard to the structural lines and surface features, such as sea-coasts and mountain ranges. To a large extent, the seismic belts are coincident with the volcanic belts, but there is sufficient divergence to prove that earthquakes and volcanoes are not necessarily associated and that the former occur in regions far from volcanoes.

Two of the principal seismic belts almost encircle the Pacific Ocean, one following the west coast of the Americas from Alaska to southern Chile. There are, however, many interruptions in this Pacific Coast belt; British Columbia, Washington, Oregon, Lower California, the northern part of the Mexican coast, and the Isthmus of Panama are seldom visited by earthquakes and no violent ones have been recorded in these areas. Even where, in a broad sense, the volcanic and seismic bands coincide, there are

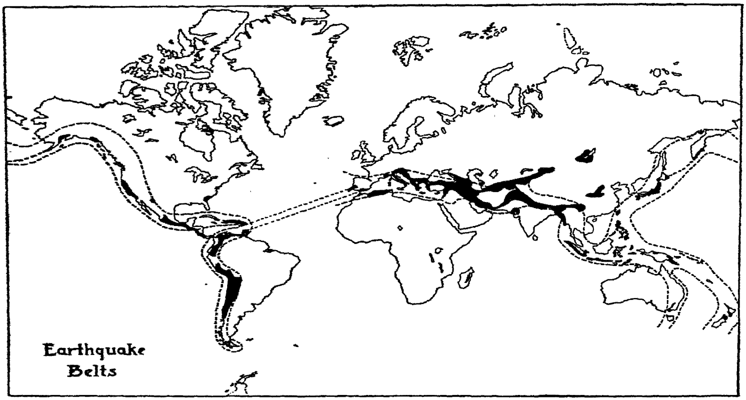

Fig. 66. — Map of earthquake belts, after de Montessus de Ballore and C. A. Reeds.

many discrepancies. For instance, the part of the California coast which has most frequently been shaken, that south of San Francisco, has had no known eruptions within the human period and, for long distances, there are not even any extinct volcanoes.

From this band is given off a loop which runs along the north coast of South America, through the Windward and Leeward Islands and Greater Antilles to Jamaica and the eastern end of Cuba, though most of that island is outside the earthquake area. The loop here described may, perhaps, be more properly referable to the third, or transverse, belt presently to be mentioned. On the west side of the Pacific, the second great belt runs down the penin-

sula of Kamchatka and the chains of islands which border the eastern shore of Asia, but not encroaching on the main land of that continent. Then the belt follows the East Indies and the islands of Polynesia to New Zealand. Whether the two Pacific bands unite in the Antarctic Sea is not known.

So far, the general coincidence in the distribution of earthquakes and volcanoes is obvious, but in the third, transverse belt, there is much greater divergence. This band pursues a somewhat irregular course in an equatorial direction, which, broadly speaking, is at right angles to that of the two Pacific bands. It seems to be interrupted by the Atlantic and Pacific oceans, but that may be because it is not yet practicable to map earthquakes on the bed of the deep sea. The Pyrenees and the south of France, Portugal, the south of Spain, and the northwest coast of Morocco are outliers of this band, which, beginning in Italy and the Alps, runs into central and eastern Asia, covering the Balkan Peninsula, the Levant, and Asia Minor. In Persia it divides, one branch passing around Afghanistan across northern India and almost reaches the Pacific; the other branch runs through central Asia. Eastward of the Mediterranean is a vast area of earthquake country, in which, for thousands of miles, there is no volcano. Japan, Greece, and Italy are the countries of most frequent earthquakes.

The map (Fig. 66) indicates the lands of frequent earthquakes, which are often of great violence. There are other regions which have been visited by earthquakes, sometimes very violent, but infrequently and at long intervals. In the years 1811 and 1812, the Mississippi Valley was frequently shaken with great violence and, as previously mentioned, only the very sparse population prevented a great loss of life. In 1886, the south Atlantic coast of the United States was shaken by the Charleston earthquake, which did great damage in that city and was felt over an area of 2,000,000 square miles. In 1884 and again in 1929, earthquakes originating in the bed of the Atlantic did great injury to the submarine cables and were quite strongly felt in Nova Scotia and Cape Breton, though not doing much damage. South Germany is the seat of many earthquakes, but none so far recorded have been violent. These are all regions where strong earthquakes are very rare and there are many large areas, such as the Great Plains of North America, the "Canadian Shield"

of crystalline rocks, and others, where earthquakes are quite unknown.

The Effects and Concomitants of Earthquakes. The direct effects of earthquakes, from the geological point of view, appear to be comparatively small, but the concomitants, which are produced by the same agencies as produce the earthquakes and accompany them, are of very great importance. In mountain regions earthquakes often cause landslips and rockslides on an enormous scale. A striking example of this is the earthquake which shook northwestern Greece in 1870, causing gigantic rockslides. Valleys are blocked in this manner and converted into lakes by damming the streams. Many new lakes resulted from the Great Indian Earthquake of 1897, and drainage lines, rivers, springs, and wells are often much changed in position by the shocks.

While the direct effects attributable to earthquakes are thus not very significant, the diastrophic forces which are the cause of earthquakes have other effects which are of the greatest geological importance. These are the sudden changes of level, which may or may not be connected with the slow process of warping considered in the preceding section of this chapter. The sudden changes which are associated with earthquakes may be upward, downward, or horizontal, and generally take place by means of *faulting* or dislocation on the two sides of a fissure. The cliff, or bluff, left standing after faulting, is called a *fault-scarp*, and great numbers of these, made in modern times, have been recorded, and similar ones have been produced in all ages of the earth's history.

Only a few of the more representative instances of modern faulting on land and in the sea-bed can be mentioned here, but it should be remembered that the number of these is very large and constantly increasing.

The violent earthquakes of 1811 and 1812 in the Mississippi Valley, which have lately been reinvestigated with very interesting results, were accompanied by a depression near New Madrid, Missouri, of 2,100 square miles, which is locally known as the "Sunk Country," and is largely flooded. Owens Valley in southeast California and east of the Sierras was violently shaken in 1872, with the formation of a fault 40 miles long and having a vertical displacement, or *throw*, varying from 5 to 20 feet. In 1887, the Sonora earthquake in Mexico and Arizona caused a fault with a

maximum throw of 20 feet, and the Sierra Teras, in Mexico, was probably uplifted in this movement, for there was a second fault, with opposite inclination, formed on the eastern side of that range, which thus seems to be a raised *fault-block* between parallel lines of dislocation. This structure is exemplified, on an immense scale, by the mountain ranges of the Great Basin in Nevada. The fault-scarp made by the Japanese earthquake of 1891 is 40 miles long and has throws more than 33 feet. In the Great Indian Earthquake of 1897 there were many changes of level, most of

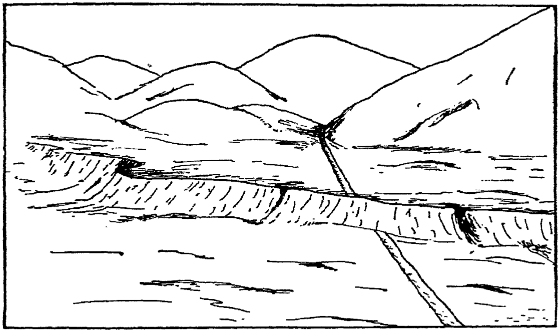

FIG. 67. — Faulting in Neo Valley, Japan, earthquake of 1891. (Milne)

which were upheavals of as much as 24 feet, though there were some depressions also. To a remarkable degree, the coast of Alaska, around Yakutat Bay, was affected by the great earthquake of 1899, in movements which were chiefly those of elevation. On the west shore of Disenchantment Bay, where the maximum uplift of 47 feet took place, adjacent points on the beach showed differences of rise of six feet or more. At the same time, the neighboring Yakutat foreland and the sea-bottom at the mouth of the bay went down as much as seven feet. In consequence of this earthquake, the Alaskan glaciers flowed with notably increased velocity for several years.

The San Francisco earthquake of 1906 was studied with unusual care by a State commission, which found that the disturbance was associated with the great San Andreas fault, which skirts the coast

of northern California, passing inland at San Francisco, whence it runs southeastward for the whole length of the state and, for an undetermined distance, into Mexico. Vertical displacements of the ground were small, not exceeding three feet, but the horizontal dislocations were, though moderate in amount, of much greater geological interest. Horizontal movements of the ground are less obvious and more difficult to detect and, for that reason, they have probably occurred much more frequently than has been reported.

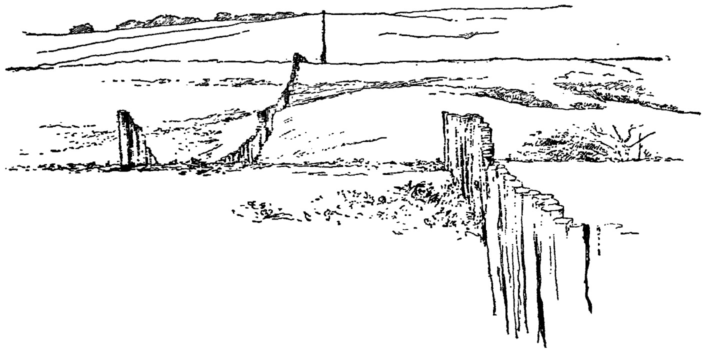

FIG. 68. — Fence broken and shifted horizontally 15 feet, San Francisco earthquake.

In 1906 conditions were particularly favorable in California for exact determination of the horizontal shifts because of the work of the United States Coast and Geodetic Survey before and after the disturbances. What seem to be permanent horizontal displacements of six to twenty feet were measured, roads and fences broken and offset by that amount; mountain peaks and the Farallones Islands, off the Golden Gate, were shifted by corresponding amounts. What was especially significant was the fact that the movement was in opposite directions on the two sides of the fault; on the eastern side, the shift was southward and on the western side it was northward.

In the Japanese earthquake of 1891, in the Neo Valley, there was, in addition to the vertical fault-scarp previously described (Fig.

67), a definite horizontal movement, as shown by several landmarks, and it appears in the offset road at the top and bottom of the scarp. Similar offsets were reported after the quake in Owens Valley, California, in 1872, in Sumatra in 1892, and in India in 1897. In the latter, railroad lines were so compressed as to be thrown into meanders (Fig. 69), which implies a shortening of the distance between the end points.

For some unknown reason, many faults in the sea-bed, which have been made in modern times, have much greater throws than those which have been reported from the land. As the sea does not wear away its own bed, except near shore, fault-scarps remain standing as lines of cliff for indefinite periods of time, and many of the scarps which have been revealed by sounding are of unknown geological dates, while others have been formed in association with modern earthquakes. The sea-bottom off Greece and the Greek islands has been much broken up in recent times, for the laying of submarine cables and repairing them after earthquake ruptures have made necessary repeated surveys of the bottom by soundings, and these have revealed some remarkable changes. A scarp of 1,400 feet in height off the west coast of Greece was found to be increased to 2,000 feet after the earthquake of October, 1893. In 1878 the cable from the mainland to Crete was ruptured in two places by a violent earthquake and the sea-floor was so broken up that it was necessary to make a long detour in relaying the cable. An earthquake in August, 1886, broke the cable from the island of Zante to Crete and, at the place of rupture, the depth of water was increased by 1,300 feet. The cable from the Lipari Islands to Sicily has been repeatedly broken at the same point.

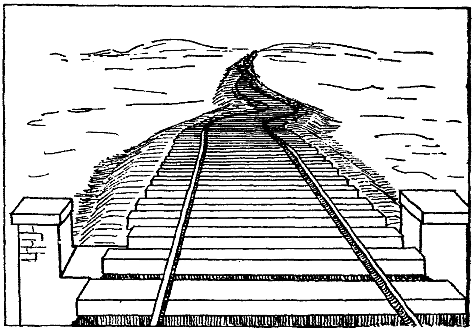

FIG. 69. — Railroad made sinuous by compression, "Great Indian Earthquake" of 1897. (Oldham)

On the North American coast several such ruptures have occurred; on October 4, 1881, three parallel cables, about ten miles apart, were simultaneously broken at the foot of the steep continental slope, 330 miles east of St. John's, Newfoundland. (Milne.)

The Grand Banks Earthquake of November 18, 1929, was especially disastrous to cables, nearly half of all those passing near Nova Scotia and Newfoundland being put out of commission;

FIG. 70.—Vein of black sand made by the earthquake of 1886, near Charleston, S. C. (Photograph by Fuller, U. S. G. S.)

no less than twenty-eight breaks of twelve cables are marked in Keith's map. "Very soon it was seen from the work of the cable ships that the disaster to the cables was much greater than was at first thought, and scores of miles of cable were abandoned, too badly broken and twisted to be worth repairing." (Keith.) The breaks were not in the shallow water over the continental shelf, but in the deep sea at the foot of the continental slope, in some places more than three miles below the surface. (See also E. M. Kindle.)

Aftershocks, such as regularly accompany great earthquakes,

were recorded by some of the seismographs and accounted for the difference in time between several of the breaks: "More than twelve hours elapsed between the widely separated eastern and western breaks on a single cable." The ruptures occurred over an area of about 370 miles north and south by 300 miles east and west. The area shaken probably extended much farther south, but there was no cable to indicate it.

FIG. 71. — Earthquake fissure filled with sand, Charleston, Mo., New Madrid earthquakes of 1811–12. (Photograph by Fuller, U. S. G. S.)

The German naval vessel *Meteor* made soundings in the south Atlantic in 1925 and, as yet, only preliminary announcements of the remarkable results have been published. Near St. Paul's Rocks, which are almost on the equator, vertical scarps of more than 2,000 feet in height were revealed. The broken-up condition of the Atlantic floor in the equatorial region had been previously reported, but it is very surprising to learn the tremendous scale upon which the faulting had been carried on. The geological date of this great series of dislocations is not definitely known, but, from indirect evidence, it may be inferred that it took place early in the Tertiary period.

Causes of Earthquakes. The immediate or proximate causes of earthquakes are, it is believed, better understood than those of the other subterranean manifestations, but the ultimate causes and the relations to those other agencies are still largely obscure.

From the point of view of causation, earthquakes are divisible into two classes, (1) the volcanic and (2) the tectonic, though it is not always possible to say to which of the two a given quake is referable.

1. *Volcanic Earthquakes* are due to gas explosions and readjustment of magmatic masses in volcanic foci. A great volcanic eruption is almost invariably preceded and accompanied by earthquakes, often of extreme violence. The shaking of the ground which precedes an eruption usually becomes more and more violent until the volcano breaks out, when the quakes diminish and die away entirely with the close of the eruption, and aftershocks seldom occur. However violent in the neighborhood of the volcano, earthquakes of this class are seldom propagated to any considerable distance and the shaken area is more or less circular in shape, with no axis greatly exceeding the others in length.

A typical volcanic quake was that which shook the island of Ischia, in the Bay of Naples, in 1883. Though terribly violent on the island, completely destroying the town of Casamicciola, with great loss of life, yet at Naples, only twenty-two miles away, the shock was hardly felt at all. The eruption of Mauna Loa in 1868 on the island of Hawaii, the most tremendous that has been observed by white men, was preceded for six days by earthquakes of gradually increasing force, until they became incredibly violent and destructive. When the eruption began, the earthquakes quickly died away. Excessively violent as these shocks were, they were almost confined to the southern half of the island and did little damage elsewhere; 150 miles away, the shocks were barely sensible. Most Central American earthquakes are of this type, as are also those at the base of Ætna, Vesuvius, and other volcanoes.

The first sign of awakening given by Vesuvius, dormant for unknown centuries, was in the year 63 A.D., when a series of violent earthquakes wrought such destruction in Pompeii that the people considered abandoning the site altogether. From this plan they were dissuaded by the Roman Senate, which voted a grant in aid of rebuilding the much-damaged city. The reconstruction was still incomplete when the final catastrophe befell the town in 79 and buried all but the upper stories of the houses out of sight. The visitor of today may see many signs of incomplete rebuilding, as well as the new construction which was under way at the time of eruption.

2. *Tectonic Earthquakes* are far more numerous than the volcanic and are produced when accumulating stresses in the earth's crust finally grow so great that the rocks are fractured and dislocated, yielding with a sudden jar, which sets up the elastic waves of an earthquake. Tectonic quakes are, in almost all instances, due to faulting, though the fault is not always visible on the surface, and are prolonged for great distances, hundreds of miles, it may be, along the line of fracture, while transversely to this line, the effect speedily dies away and ceases. The shocks may be due to renewed movements along an old line of fault or to the formation of a new one. The California earthquakes of 1868, 1872, and 1906 are all referable to the great San Andreas fault.

The careful study of the quake of 1906 suggested the *elastic rebound theory* of tectonic earthquakes, as it is named by Professor H. F. Reid. For an unknown period the rocks in California along the San Andreas fault have been subjected to cumulative stresses, until, in April, 1906, the resistance of the crust was overcome and then came a new fracture or a sudden slip along an old one. The crust, suddenly relieved of the stress, snapped back towards its original position, with a jar that set up the elastic seismic waves of the earthquake. As already mentioned (p. 170), the movement of the ground was in opposite directions on the two sides of the fault, as it also was along the fault line of the Japanese quake of 1891. The elastic rebound theory explains the phenomena of tectonic earthquakes very well, though it is severely criticized by some authorities.

Areas where great heights of land pass by very steep grades to great depths of sea are particularly regions of frequent and violent earthquakes, because on these steep slopes the rocks are under perpetual stress of gravity, tending to pull them down into the deeps. The west coast of South America where very high mountains are near the shore-line, and so narrow is the continental shelf that the deep sea is within ten miles of the land, is the seat of many and violent earthquakes. In the south Pacific, the Tonga submarine plateau, from which rise the Tonga and Kermadec Islands, has the profound abyss of the Tonga Deep at its eastern side. Similarly, near the eastern edge of Japan is the Tuscarora Deep, in which soundings of 4,655 fathoms have been made. All these areas are subject to most violent earthquakes, in remarkable contrast to the Atlantic coasts of North and South America,

western Europe, and eastern Australia, where earthquakes are relatively rare and where the slopes are only one-third to one-tenth as steep as along the Pacific. In the Grand Banks Earthquake of 1929, and that of 1884, which were so destructive to the cables, the breaks were not along the continental shelf, but in deep water at the foot of the continental slopes.

To this extent, earthquakes have been reasonably explained, but the further question, how the stresses within the earth's crust are generated, cannot yet be definitely answered. Until a few years ago, the solution of this problem seemed to be quite simple; the earth was believed to be losing heat by radiation and therefore to be contracting. Contraction produced the stresses, which, in turn, were the cause of earthquakes, diastrophism, crumpling and folding of the rocks, the formation of mountain ranges, and many minor phenomena. When the rocks yielded gradually and without fracture, diastrophic upwarping and downwarping resulted; when they resisted until stressed beyond their strength, the sudden fracturing produced earthquakes, and the changes of level and position associated with earthquakes resulted.

The contraction theory, which seemed so satisfactory an explanation of many geological processes, has been, to a great extent, abandoned by geologists. The problem cannot be further discussed here, but it will be shown in subsequent chapters (XVIII and XXI) that the abandonment is perhaps premature and that it may be necessary to return to this conception.

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CHAPTER X

THE SEDIMENTARY ROCKS

The sedimentary rocks are especially characterized by their *stratification,* or division into parallel layers or beds, essentially different from the massive structure of the igneous rocks. In the first instance, at least, the materials of which the sedimentary rocks are made up were derived from the chemical decomposition or mechanical disintegration of the igneous rocks. The component minerals are therefore simpler, more stable, under the conditions obtaining at and near the earth's surface, and very much fewer in number than those of the igneous rocks. Sometimes, igneous minerals pass over into sedimentary rocks without other change than comminution, such as the flakes of mica, which are found in many sandstones. Save in the case of quartz, however, these minerals are insignificant in quantity. Quartz, being very hard and extremely simple and stable chemically, is not subject to decomposition in nature and is the only mineral which occurs largely in all three classes of rock. The principal minerals of the sedimentary rocks are quartz, clay, and calcite, more or less mingled with other minerals.

Though the chemical precipitates are crystalline, being deposited from solution in water, the overwhelming majority of sedimentary rocks are made up of pieces of older rocks of all sizes, from microscopic fineness to great boulders of many tons weight. They are, therefore, said to be *fragmental,* or *clastic,* in texture; thus sedimentary, fragmental, clastic, secondary, derivative, stratified, are all synonymous terms and are interchangeably used, though there are shades of difference among them and none of them is entirely satisfactory.

Such igneous rocks as contain quartz yield that mineral without further change than breaking up into smaller pieces. Clay is derived principally from the decomposition of the feldspars, but other minerals containing the silicates of aluminium also give

rise to clay. Mud, which is the name for mixtures of minerals in a very fine state of subdivision, but not decomposed chemically, is also an important constituent of sedimentary rocks. Calcite and other calcareous minerals of the sedimentary rocks, though ultimately derived from igneous rocks, are usually accumulated by organic agencies, and the immense masses of carbon and the hydrocarbons, which are of such enormous economic importance, are likewise of organic origin.

Because of the manner in which their materials are supplied, sedimentary rocks are called secondary, or derivative, rocks. They are laid down, for the most part, under water, though wind-made accumulations on the land are also of some geological importance, and the manner of their formation, as will be subsequently explained, produces stratification, or bedding, as a necessary consequence. Deposits made by flowing ice, or glaciers, are not stratified, being exceptional among sedimentary deposits. Sediments accumulate in all sorts of water bodies: in rivers, lakes, and, above all, in the sea. The mode of deposition is (1) mechanical, the manner in which by far the largest number of sedimentary rocks have been formed; (2) by chemical precipitation, a comparatively unimportant method; (3) by organic accumulation, a method which, though of supreme economic importance, is quantitatively much below the mechanical method of deposition.

The classification of the sedimentary rocks is, at present, made according to their mode of formation and, secondarily, according to their chemical constitution, but this scheme is unsatisfactory and will probably be replaced by a better one, as knowledge becomes more complete.

A. Aqueous Rocks

The rocks which were accumulated under water and, especially, under the sea are by far the largest part of the sedimentary class.

I. Mechanical Deposits

These have been formed by the accumulation of débris, derived from the destruction of preëxisting rocks, carried in mechanical suspension by moving water, streams, waves, or currents, and dropped when the velocity of the water was no longer sufficient to carry them. The particles, or fragments, large or small, are

usually more or less rounded by abrasion and are sorted according to the coarseness or fineness of the fragments. The sorting is often surprisingly complete, both as to the size of the particles and their chemical composition, but often mixtures occur and the transition from one kind of sediment to another is so gradual as to be imperceptible. The study of the processes now in operation will show that mechanical deposits are forming at the present time and in bodies of water of all kinds, and similar accumulations have been made since the beginning of recorded geological time. Chemically, mechanical deposits are of two principal kinds: *siliceous*, or sandy, and *argillaceous*, or clay and mud.

1. SILICEOUS ROCKS

The rocks of this group are formed predominantly of quartz in various states of subdivision. Of the rock-forming minerals, quartz is the hardest and most indestructible and hence in the wear of a river channel, or by the pounding of surf on a beach, quartz will be reduced to pebbles and sand, when the more destructible, associated minerals are ground into fine silt, or decomposed into clay. Small quantities of other minerals, in fine particles, are frequently present in siliceous accumulations.

1. *Sand* is a loose, uncompacted mass of quartz grains, coarse or fine and more or less angular. River sands and those formed by the atmospheric disintegration, or *weathering*, of rocks commonly have more angular grains, because of the splitting of the quartz fragments along preëxisting flaws. Desert and wind-blown sands have more rounded and finer grains, due to mutual attrition, and, under the microscope, many of the grains are seen to be pitted. Beach sand is somewhat rounded by the grinding of the waves.

Properly speaking, the term *sand* should be used only for loose, granular masses of quartz fragments, but any granular aggregation may be so called, because it resembles sand in appearance. Thus, we have shell sand and coral sand, which are made of calcareous grains, and green sand, a mass of glauconite grains; without prefix, the word *sand* means quartz grains.

2. *Sandstone* is a rock of varying degrees of hardness, which is made up of grains of sand held together by some cementing substance. The commonest cements are the oxides of iron, calcium carbonate, and silica. The sandstones with calcareous cement weather rapidly and crumble into sand. Ferruginous sandstones

are cemented with iron compounds, usually hæmatite (Fe_2O_3) or limonite ($2\,Fe_2O_3 \cdot 3\,H_2O$), and are more brightly colored red, yellow, brown, or gray. These rocks are much more durable than the lime-cemented sandstones and yield excellent building stone, but, under soil and near the surface, the iron cement is dissolved and the rock disintegrates. Most durable and hardest of all are the sandstones with silica cements.

Varieties of sandstone are produced by the conspicuous admixture of other minerals. A *micaceous sandstone* is one with flakes of mica deposited along the stratification planes. *Argillaceous sandstone* is one composed of finer sand grains than the more typical sorts, contains a considerable quantity of clay, and is, in general, more thinly bedded. The *flagstones*, so largely used for paving, are examples of such rock; they may be split into slabs of almost any size and thickness. *Feldspathic sandstone*, or *arkose*, is composed of varying proportions of finely divided feldspars mingled with sand and cemented into hard rock. Sometimes the material is almost entirely feldspathic.

3. *Graywacke*, a naturalized German word "applied to feldspathic or tuffaceous grits and coarse sandstones, usually dark in color, which are strongly cemented . . . and occur characteristically among the older formations." This is the ordinary definition (Holmes); quite a different one is the following:

"A variety of sandstone composed of material derived from the disintegration of basic igneous rocks of granular texture, and thus contains abundant grains of biotite, hornblende, magnetite, etc. It is the ferro-magnesian equivalent of arkose." (Twenhofel.)

4. *Gravel* is a mass of pebbles, varying in size from a pinhead to a cobblestone; very coarse gravel, of cobblestone size, is called *shingle*, especially in England. Pebbles are most frequently of quartz, because of the superior hardness of that mineral, but they may be of almost any rock material that is not too soft. Pebbles of slate, limestone, sandstone, and the like are commonly flat and discoidal, being pushed along the bottom and worn on one side, then turned over and worn on the other. The gravel beach on Lake Ontario, shown in Fig. 157, is covered with flat, discoidal pebbles. Pebbles of quartz, granite, and other hard materials have a rudely spheroidal shape. They have been rolled over and over, as one may see by watching a retiring wave on a sloping beach. Gravels with rounded pebbles are made by streams, lakes, and the

sea, and thus may be found extensively in both marine and fresh-water deposits. Desert pebbles are characterized by their peculiar shapes, produced by the drifting sand. Elongated shapes and angular edges (*Dreikanter* in German) are due to wind sculpture.

5. *Conglomerate* (or pudding stone) is cemented gravel, the pebbles embedded in a matrix of consolidated sand. The proportions of the two constituents vary from a pebble sandstone to a pudding stone with very little sand. Different names are given to conglomerates in accordance with the material of the pebbles, as *quartz conglomerate, flint conglomerate, limestone conglomerate, granite conglomerate*, etc.

6. *Grit* is a hard, densely cemented conglomerate of very small pebbles. Such rocks were once much used for millstones.

7. *Breccia* is a cemented mass of stone fragments, which differ from the pebbles of a conglomerate in being angular, not rounded and water-worn. The fragments may be of any kind of rock and the matrix is deposited between the fragments from mineral matter in solution. *Fault Breccia* is made by the grinding together of the two walls of a fault, detaching great numbers of angular fragments, which are subsequently cemented, usually by calcite.

8. *Till*, or *Boulder Clay*, is the unstratified drift deposited by glaciers, made up in irregular mixture of fine and coarse particles, pebbles, cobbles, and great boulders.

9. *Tillite* is a geologically ancient till which has been cemented into a firm rock, and may have been folded, jointed, and cleaved.

2. ARGILLACEOUS ROCKS

1. *Clay — Mud.* Clay consists of kaolin, etc., in various proportions, but nearly always with large admixtures of other minerals. Kaolinite is hydrated aluminium silicate and is derived chiefly from the chemical decomposition of the feldspars and feldspathoids. The great economic importance of clay is due to its plasticity and to its becoming hard and solid when fired at a temperature high enough to expel the water of composition. Clay occurs in very different degrees of purity. *Kaolin*, or porcelain clay, is nearly pure. *Potter's clay* contains a quantity of very finely subdivided sand and other substances; earthenware and stoneware are made from this. *Brick clay* may have as little as 14 per cent of kaolin, sand and compounds of calcium, magnesium, and iron making up the rest. When considerable iron is present, the

bricks turn red on firing, whatever the color of the clay, because the ferrous iron is oxidized to hæmatite. The iron, magnesia, and lime in brick clay act as fluxes and cause the clay to fuse at much lower temperatures than kaolin will do. Even in the relatively moderate heat of brick-kilns the bricks may be made to fuse on the outside and thus glaze themselves. Such *semi-vitrified* bricks, as they are called, are exceptionally hard and are extensively used for paving in regions where there is no stone.

2. *Fire-clay* is a nearly pure mixture of clay and sand, the fluxes, iron, magnesia, and lime being absent, or present in very small quantities. Such a clay burns to white or very pale buff bricks, which will endure very high temperatures and are used to line stoves and blast furnaces. An open fireplace backed with ordinary red brick will disintegrate and crumble after a few winters, while one lined with fire-brick will last indefinitely. Fire-clay very generally is found beneath coal-seams, being the ancient soil in which the coal plants grew. Such ancient soils are often hard rocks and must be ground up for use.

3. *Mud* differs from clay in having no definite chemical composition, being composed of many finely subdivided minerals. The muds which are deposited on the sea-floor in moderately deep water are, for the most part, made up of a mineral flour, without decomposition of its constituents; on land, wet soils, other than sandy ones, are called mud. Wet mud is less plastic than clay and, when fired, does not harden and solidify, but crumbles to dust.

4. *Mudstone* is a rock composed of hardened clay, or feldspathic mud, or a mixture of both, with more or less other minerals also. When exposed to the weather, mudstone breaks down rapidly.

5. *Varved clays* occur on a very extensive scale in glaciated lands in both northern and southern hemispheres; the conspicuous banding is due to seasonal deposition which took place in glacial waters in summer but ceased in winter. Varve is a Swedish word and means the deposit of a season, whether of winter and summer, wet and dry seasons, high and low water, or other regularly recurrent conditions of weather. Varved clays and shales are typically those deposited in glacial waters, but also were formed in lakes and, in some cases, are of very great geological antiquity.

6. *Shale* is a finely stratified or laminated clay, or mud rock, formed by the consolidation of mud and silt. Paper shales are so called because the laminæ are no thicker than sheets of stout paper

and often represent varves. The Green River Shales of Wyoming, Colorado, and Utah, which are of early Tertiary age, are very conspicuously banded, with 30 or 40 laminæ to the inch; these are interpreted as non-glacial varves. Most shales are quite soft and weather into innumerable fragments, but some are very hard and so durable as to be valuable building stones. *Bituminous shale* is colored dark or black by organic matter. *Oil shale* yields petroleum on distillation, and when occurring in quantity, forms a valuable reserve supply. Ordinarily, shales contain more or less fine sand and, as this increases in quantity, they pass gradually into arenaceous shales and argillaceous sandstones, or, by increase of calcareous matter, into limestone.

7. *Argillite* is a clay rock which is very much harder and denser than shale and in which the lamination is less distinct. The cementing substance is either silica or one of the many iron silicates, and the rock is so hard that the pre-Columbian Indians of the Delaware Valley used it for weapons in place of flint.

8. *Marl* is a clay containing calcium carbonate in large proportion; exposed to the weather it rapidly crumbles. In New Jersey, the term *marl* is inaccurately applied to the so-called green sand, itself a misnomer, for it is composed of grains of glauconite, not quartz.

II. Chemical Precipitates

The rocks of this group are, with few exceptions, of restricted extent, and not at all comparable to the great masses of mechanical and organic accumulations. Precipitation from solution takes place conspicuously only around the mouths of certain classes of springs and in salt and saline lakes that have no outlet. There is some precipitation in the sea, but relatively on a very small scale.

1. PRECIPITATES OF THE ALKALIS AND ALKALINE EARTHS

1. *Calcareous Tufa*, or *Sinter*, *Travertine*, *Stalagmite*, *Onyx Marble*, are all forms of calcium carbonate deposited from solution in water around springs, in streams and lakes, and, in limestone caverns, by waters percolating through the roof. The deposits consist of calcite, or, sometimes, of aragonite, are often very pure and of a white color and more or less translucent, though they may be stained by other substances. In structure they are banded and stalactites show rings of growth; often a travertine incloses in-

numerable small cavities, as in the rock from Tivoli, near Rome, which has been so largely used as a building stone in both ancient and modern times. The so-called "Mexican onyx," or "onyx marble," is a beautifully banded, translucent travertine found in ancient spring deposits. The terms *calcareous tufa* or *sinter* are synonyms of travertine.

Travertine is of small extent, but immense thicknesses of it may be accumulated, as at Tivoli. In the Yellowstone Park are the famous travertine terraces of the Mammoth Hot Springs, where microscopic plants are largely concerned in forming the precipitate and in producing the remarkable colors of the active part of the deposit. Where the water no longer flows, the travertine is snowy white and speedily crumbles under the action of the weather.

2. *Oölite* is a limestone made up of minute spherules of calcium carbonate, cemented into a compact mass, somewhat resembling fish-roe, whence the name, which means "egg-rock." Each spherule is composed of concentric layers of calcite, deposited from solution around some nucleus, such as a particle of sand, or dust, or a calcareous fragment. The beach rock of a coral reef is made in this way and travertine often has an oölitic structure. When the spheres are larger, like peas in size and shape, the rock is called a *pisolite*.

3. *Gypsum* ($CaSO_4 \cdot 2\,H_2O$) is a salt lake deposit and resembles a limestone in appearance, but is much softer. White when pure, it is often stained gray, brown, or red by iron solutions, or black by organic matter. The beds are compact, fibrous, or crystalline-granular and portions of the beds may be made up of transparent crystals of selenite. When heated so as to drive off the water of composition, the gypsum becomes the familiar plaster of Paris. More or less associated with gypsum are deposits of *Anhydrite* ($CaSO_4$), the anhydrous sulphate which, when made in the laboratory, is precipitated from hot solutions.

4. *Rock Salt* ($NaCl$) is thrown down from the dense brine of salt lakes, when evaporation has concentrated the solution to the proper degree, and follows the deposition of gypsum, which explains the very common association of the two in successive beds. The salt may be present as an ingredient of shale (saline shale), or in thin layers, indicating brief periods of deposition, followed by freshening of the water. It may also occur in enormously thick masses from which commercial salt is obtained by refining. Under

the North German plain, Poland, and Austria are immense bodies of salt, the thickness of which is unknown, as borings of 4,000 feet have failed to pass through them. When pure, rock salt is transparent and colorless, but frequently it is stained by iron or mixed with fine mechanical sediments.

5. *Potassium Salts.* A few deposits of rock salt, such as those of Prussia (at Stassfurt), Alsace, and Cordova in Spain, are capped by compound chlorides of potassium, magnesium, and calcium, which must have required evaporation to complete dryness, since the chlorides of potassium, calcium, and magnesium are so extremely soluble that lumps of them dissolve in the water which they absorb from the air. The important potassium-bearing minerals in the salt beds are Sylvin (KCl), Carnalite (KCl, $MgCl_2$, $6\,H_2O$), Kainite (KCl, $MgSO_4$, $3\,H_2O$), Polyhalite ($2\,CaSO_4$, $MgSO_4$, K_2SO_4, $2\,H_2O$). These minerals usually occur mingled with more or less rock salt, seldom by themselves. Before the World War, the Germans had a monopoly of commercial potash, so indispensable in agriculture and many industrial processes, and the very high prices consequent on the blockade made possible the exploitation of sources of potash which, in time of peace, would be altogether unprofitable. On the Pacific Coast, kelp, a seaweed, was used, as were the saline lakes of Nebraska and the green sand beds of New Jersey. Deep borings in Texas and New Mexico indicate the existence of potassium compounds in the salt bodies.

6. *Green Sand.* As already indicated, this term is a misnomer, given because of the granular nature of the material. The grains are soft and friable and consist of the mineral glauconite, a hydrated silicate of iron and potassium.

2. SILICEOUS PRECIPITATES

These are comparatively so rare and of such small extent that they hardly deserve the name of rocks.

1. *Geyserite*, or *Siliceous Sinter*, is deposited from solution in the hot alkaline waters of geysers, themselves a very rare phenomenon. Deposition is due partly to evaporation of the water, partly to the action of Algæ. In the Yellowstone Park the geysers have built up quite extensive terraces of this hard, flinty rock.

2. *Chert* (*Flint* or *Hornstone*) forms exceedingly dense and fine-grained masses which, under the microscope, are seen to be made

up of very minute grains of chalcedony and crystals of quartz, with more or less amorphous silica. The mode of origin of these masses has not been satisfactorily explained, but, in many instances, they were formed in the sea.

3. FERRUGINOUS PRECIPITATES

1. *Bog* and *Lake Iron Ore.* Ferrous carbonate ($FeCO_3$) is soluble in water containing carbon dioxide; springs containing sufficient quantities of dissolved iron to be perceptible to the taste are called *chalybeate.* In lakes and open waters, where the iron solutions are brought into contact with the air, the carbon dioxide is given off and the iron oxidized to hæmatite or limonite. At the bottom of bogs, where there is little free oxygen, the iron is deposited by concentration as siderite ($FeCO_3$).

2. *Marine Iron Ores.* The formation of iron ores upon the bottom of the sea has not been observed in Recent times, but in ancient sedimentary rocks immense deposits of iron ore are found under conditions which point to precipitation on the sea-floor, chiefly of hæmatite, but also of siderite. Excellent illustrations of these marine ores are found in the Clinton stage of the Silurian system, interstratified and embedded in ordinary sediments, chiefly shales and sandstones, are oölitic and "fossil" hæmatites, the spherules and grains of which are made up of concentric shells, like those of the calcareous oölites. In the Ordovician of Newfoundland the Wabana ores are very much like those of the Clinton stage, oölitic in structure and consisting chiefly of hæmatite and some siderite. There can be no doubt that they were formed in the same way, and in both the Clinton and the Wabana, the iron is deposited, in concretionary fashion, around fragments of fossil shells, quartz grains, or other nuclei. The important clay-ironstone ores of the Cleveland district in England are siderites mixed with clay and are of marine origin.

III. Organic Accumulations

The organically formed rocks are those of which the materials were accumulated by animals or plants. After the death of the organisms, more or less of their substance was preserved, added to by successive generations, and finally compacted into rock, sometimes extremely hard. The processes of accumulation may

be observed to-day in peat-bogs on land, in lakes, and in the shell-banks, coral reefs, limestone plateaus, and organic oozes of the sea. Similar processes have been going on in all the recorded periods of the earth's history since the first appearance of life on the earth, and many organically formed rocks, of vast extent and thickness, are now a part of the earth's solid crust.

I. CALCAREOUS ACCUMULATIONS

1. *Limestone* is a very common and widely distributed rock, of great economic importance. It is composed of calcite ($CaCO_3$) in different degrees of purity, from 40 per cent to more than 98 per cent, and varies greatly in hardness, fineness of grain, and degree of crystallization, for limestone is the only sedimentary rock, not precipitated from solution, which is often crystalline. Calcite frequently crystallizes from the action of water, as may be observed in modern examples, and thus a crystalline limestone is not always a true marble (*q. v.*). Sand or, more frequently, clay is a common impurity and, by gradual increase of clay, a bed of limestone may be traced laterally into shale and an arenaceous limestone into a sandstone.

In many varieties of limestone, the organic nature of the rock is very clearly shown, shells, corals, crinoid stems, Foraminifera, and the like appearing conspicuously, especially on weathered surfaces. Sometimes the organic nature of the rock can be demonstrated only with the microscope, and often the calcareous materials have been so completely ground up by the action of the waves, or so reconstructed by crystallization, that all trace of organic structure has been destroyed. The example of the crystalline rock now forming in coral reefs clearly indicates that the absence of organic structure, even microscopic, is no proof that the rock is not of organic origin. Aside from Pre-Cambrian rocks of uncertain origin, the great limestones of wide geographical extent are all of marine origin, in striking contrast to the travertines and other chemical calcareous deposits which are always local, although, as at Tivoli, they may be very thick.

As a rule limestones are laid down in deeper water than sandstones and shales, but not necessarily so, freedom from large amounts of clastic material being more important than depth of water or distance from land. In the Gulf of Mexico and in the Bahamas are great calcareous banks, such as the Pourtalès Pla-

teau, which form in quiet shoal water, and reef-corals cannot grow in water more than twenty fathoms in depth.

No satisfactory classification of limestones has yet been made; mode of formation, purity, texture, and the nature of the organic material are all employed for different purposes.

2. *Shell Marl* is an incoherent and crumbling rock formed from the accumulation of fresh-water shells at the bottom of lakes and ponds. When found, as it often is, beneath a peat-bog, in which molluscs cannot live, the shells indicate that the bog was made from a pond, or lake, by the growth of plants. When the shells are cemented together into a firm rock, it is called a *fresh-water limestone*, but such rocks are of small extent and thickness in comparison with those of marine origin.

3. *Chalk* is a soft, earthy limestone, frequently very pure and white, pale gray, or buff in color. Chalk dust, under the microscope, is seen to be made up of the shells of Foraminifera, closely resembling the *Globigerina* oozes now forming on the sea-floor at depths of 400 to 2,900 fathoms. There is one important difference, however; chalk is not a deep-sea deposit, but, as is shown by the fossils contained in it, was accumulated in water of moderate depth. A chalk-like deposit is found in certain coral reefs, formed by the consolidation of finely comminuted coral mud, but, microscopically, this deposit is entirely different from true chalk.

The greater part of the limestones is of animal origin, but the calcareous sea-weeds, which are so like corals in appearance that they were formerly supposed to belong to that group, have contributed very largely to the making of limestones. It is not definitely known whether chemical precipitation of calcium carbonate takes place in the deep sea. In shoal water, near the mouths of rivers which carry large quantities of $CaCO_3$ in solution, such precipitation is known to occur, but there it is rather a cement for sandstone than a calcareous deposit. The rôle of bacteria in forming calcareous deposits in the sea is still debatable.

4. *Dolomite* and *Magnesian Limestone* are rocks which are still imperfectly understood. They are composed, in varying proportions, of calcium and magnesium carbonates, $MgCO_3$; nearly all limestones contain some magnesium carbonate, but the name *dolomite* is used only for those rocks which have a large magnesian content. The rock may be composed entirely of the mineral dolomite, which is a double carbonate; in such a case the proportions

of the two carbonates are $CaCO_3$ 54.35 to $MgCO_3$ 45.65, but such rocks are rare and nearly always there is a greater or less admixture of calcite, and magnesian limestone is the term employed for low percentages of magnesium.

Most of the great dolomites which are found in formations of nearly all the principal divisions of geological time were originally marine limestones of ordinary type and were converted into dolomites subsequently by solutions of magnesium salts, since no marine animals have shells or tests with so high a proportion of magnesian carbonate. Dolomitization may be observed as going on in the lagoons of coral reefs at the present time and the lower parts of many modern reefs are dolomitic, but the method of effecting the change is not well understood. So far as the great, organically formed limestones are concerned, dolomitization must have taken place after the formation of the rock. In the famous Dolomites of the Tyrol, the coral reefs in the Triassic limestones have been dolomitized, a process facilitated by the composition of coral, which is aragonite, and that is much more easily transformed than calcite. "The Carboniferous Limestone of England is also considerably dolomitized locally, and it has been noticed that this is specially prone to occur in the neighborhood of large open joints, where water can circulate freely." (Rastall.)

On the other hand, there is evidence that certain dolomites have been formed by chemical precipitation in salt lakes, especially those associated with rock-salt and gypsum, or anhydrite, as in the Triassic of central and southern Germany, and the same is, by some authorities, believed to be true of the great magnesian limestone of Durham, in England. "It seems clear that the Magnesian Limestone as a whole originated in a basin of the Caspian type, since it contains marine fossils, and that that basin became more and more desiccated, till finally the highly arid conditions of the Trias prevailed." (Rastall.)

2. SILICEOUS ACCUMULATIONS

The siliceous deposits of organic origin are much less common and far less extensive than the calcareous, because comparatively few animals or plants secrete shells or tests of silica.

1. *Infusorial Earth* is a fine white powder composed of the microscopic tests or frustules of the one-celled plants called diatoms. The extreme fineness and hardness of the minute parti-

cles make this an excellent polishing powder. A celebrated deposit of this character occurs at Richmond, Virginia.

2. *Siliceous Oozes*, such as are now forming in the profoundest depths of the sea, are made of the tests of Radiolaria. These are extremely rare as rocks of the land. When thoroughly consolidated, Radiolarian oozes form cherts, the nature and origin of which are shown by the microscope. Very ancient rocks of this sort occur in the Alps and in Brittany and compacted deep-sea oozes, now on land, surround the Banda Sea of the East Indies, and in certain of the West Indian islands, notably in Barbados.

3. *Flint* or *Chert* occurs in nodules or beds, especially in marine limestones, though sometimes it is found in fresh-water deposits. The microscope sometimes reveals sponge spicules and other siliceous organisms in chert and flint, but not always, and the structureless cherts are believed to have been precipitated from solution. The radiolarian cherts were considered in the preceding paragraph.

3. CARBONACEOUS ACCUMULATIONS

The rocks of this group are formed principally, and perhaps altogether, from vegetable matter which has undergone partial decay under water. As a result of progressive decomposition, the gaseous constituents of the plant tissues are diminished, while the *proportion* of carbon rises. This is not because the carbon increases, but because it is much more slowly removed than the hydrogen, oxygen, and nitrogen. Aside from petroleum, all varieties of carbonaceous rocks shade very gradually into one another, and from fresh vegetable matter to the hardest anthracite coal, there is an unbroken series of transitions, though it may be that instead of one such series there are several parallel ones, due to differences of original constitution.

1. *Peat* is a partially carbonized mass of vegetable matter, such as accumulates under water in a bog. The fragments of plants are clearly shown and identifiable, but some of the material is a fine black mud, carbonaceous and yet so thoroughly macerated as to show no structure, even under the microscope. This is called *sapropel*. Peat is much used as a fuel in open-grate fires, in countries where coal and wood are rare and costly, but is not suited to industrial uses.

2. *Lignite* or *Brown Coal* is more advanced in decomposition, is harder and more compact than is peat, and its vegetable struc-

ture is less clearly shown, though still sufficiently obvious. The lignites are, for the most part, of later geological date than the true coals and are inferior as fuel; nevertheless, they form reserves of great value. The brown coals of Germany occur in beds of incredible thickness, as much as three hundred feet, and are of early Tertiary age (Oligocene epoch), and in North America they follow the Rocky Mountain area from Texas into Canada and are, for the most part, of late Cretaceous date of formation.

3. *Coal* is a compact, more or less hard, black or dark brown rock, in which vegetable structure cannot be detected by the unassisted eye, though the microscope seldom fails to show it. Coal occurs in beds, or strata, or "seams," as they are variously called, interstratified with shale, sandstone, and, much less frequently, with limestone. The roof of a coal seam is usually a shale, made black by saturation with carbonaceous material and bearing numerous plant-impressions. In the great majority of instances the coal-bed rests on a "seat-stone," evidently an old soil with fossil roots, and consisting either of a fire clay, or a siliceous bed, compacted into hard rock. Thick beds of coal are often subdivided by very thin "partings" of sediment; it may be merely a film of clay. Very frequently, however, a parting thickens in one direction until it becomes a thick stratum. Thus, what is in one area a thick seam of coal may be traced continuously into another area, where the seam becomes several coal beds, separated by clastic sediments.

The various kinds of coal vary much in hardness, structure, and chemical composition, but with the exception of cannel and boghead, they are all connected by intermediate gradations.

Bituminous Coal, commonly called *soft coal*, is a term that covers many varieties, differing much in their value for different purposes. Disregarding the ash, bituminous coal has from 70 to 80 per cent of carbon and 20 to 30 per cent of volatile matter, chiefly hydrocarbons. When heated in a closed retort, the volatile matters are driven off as illuminating gas, coal tar, etc.; the hard residue, which is extremely porous, is *coke*, called gas-house coke, to distinguish it from that made in coke-ovens. Such soft coals as yield a good quality of coke are called *coking coals* and may not differ in chemical composition from those which will not coke. The difference is physical; coke must be hard and strong enough to support the weight of the layers of ore, fluxing limestone, and fuel in a

blast furnace. Observations have been made tending to show that coking coal is largely made up of woody tissue, but whether this is generally the case remains to be discovered.

4. *Anthracite* is a hard, lustrous coal, that, aside from the ash, is nearly pure carbon, with very little volatile matter; it burns without smoke or flame and gives an intense heat. *Semi-bituminous*, or *Steam Coal*, is intermediate in character and composition between anthracite and bituminous; it burns with a long flame, which is very effective in the tubes of steam-boilers, whence its common name.

5. *Cannel Coal* forms a very distinct variety, which does not fit into the series just enumerated. It occurs in lenticular patches, not in beds, and, though light and not very hard, is yet compact; under the microscope it is difficult to detect any vegetable structure. Cannel has 70 to 85 per cent of carbon and the remarkable proportion of 6 to 7 per cent of hydrogen, burning with a white, candle-like flame, which gives its name to this coal. Differing from what may be called the normal coals, cannel frequently contains fossil fish, which indicates an unusual mode of formation.

The following table (from Kemp) gives the composition of the typical coals, excluding ash:

	C	*H*	*O*	*N*
Wood	50	6	43	1
Peat	59	6	33	2
Lignite	69	5.5	25	0.8
Bituminous Coal	82	5	0.3	0.8
Anthracite	95	2.5	2.5	trace

While there is practical unanimity of opinion that coal is formed from accumulations of vegetable matter, there is less complete agreement as to the manner in which those vast accumulations were made. It must be remembered that a bed of coal has been greatly reduced in volume from the original vegetable substance, partly by the loss through decomposition, partly by compression from the weight of overlying material, and, frequently also, by the diastrophic compression of folding. So great is this loss, that a bed of bituminous coal represents only about one-fourteenth of the thickness of the original mass of dead plants.

Many theories have been propounded to explain the formation of coal, but only two of these need be considered here.

Peat-bog Theory. American geologists are agreed that coal was derived from peat, which was accumulated in bogs, such as the

existing Great Dismal Swamp of Virginia and North Carolina, and that in North America there is no known instance of coal beds (other than cannel and boghead) which is not best explained in this way. The vast extent, hundreds or even thousands of square miles in area, the uniform thickness of individual coal seams, and their complete freedom from sedimentary impurities, such as sand or clay, are very strong evidence for this theory. Additional weight is given to this view by the seat-stone or under-clay, which is seldom wanting beneath a coal seam. This is an ancient root-filled soil and, in many instances, tree-stumps, connected with these roots, rise up through the coal, which was accumulated around them, just as peat is now formed around the trunks of the cypress trees in the Dismal Swamp.

Progressive differences in coal are, on this theory, explained as stages of incipient metamorphism. Figure 72 illustrates this very convincingly, tracing a single bed of coal, the great Pittsburgh Seam,

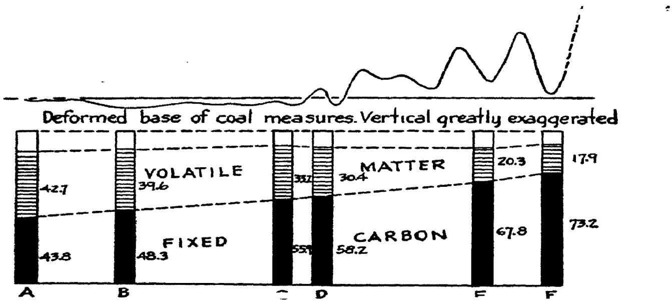

FIG. 72. — Diagram showing composition of the coal of the Pittsburgh Seam on a line from Ohio to near Cumberland, Md. *A*, at a mine 25 miles west of Wheeling, W. Va.; *F*, near Cumberland. (M. R. Campbell)

from Ohio to the neighborhood of Cumberland, Maryland. The proportion of fixed carbon steadily rises and that of volatile matter as steadily diminishes as the coal bed is traced eastward from a region of horizontal, undisturbed strata into the compressed and folded beds of the Appalachian Mountains.

Another interesting example is afforded by the Ozark dome in Missouri and Oklahoma which has exerted a relatively gentle com-

pression upon the surrounding coal fields. The more nearly the uplift is approached, the less is the moisture content of the coal; it almost follows the formula, that the percentage of moisture is directly proportional to the distance from the uplift. Mr. M. R. Campbell, to whom these examples are due, distinguishes eight stages of metamorphism in coal.

The French Theory. The peat-bog theory of coal accumulation is accepted by most German and English geologists, but not by the French, who have a different explanation, at least for certain of the coal beds of France. According to this view, the vegetable matter was accumulated in lagoons, not in bogs, and much more importance is ascribed to the original character of the vegetable matter accumulated to form a given coal than to subsequent metamorphic processes. The two views are not mutually exclusive, and every coal field must receive its own explanation, though any variety of coal sufficiently metamorphosed will be converted into anthracite.

Coal is always interstratified with other beds, usually of clastic sediments, sometimes of limestone. This implies that the bogs were flooded from time to time either by fresh or salt water, and sediment deposited upon the surface of the peat. It is not necessary to suppose that the coal basin was repeatedly rising and falling; a general downward movement, with long pauses, will also account for the facts. When the bog was flooded on account of a depression, which gave access to the sea or to fresh waters, the deposition of sediment built up the surface, until a fresh-water bog could be reëstablished. In some sections, as in Nova Scotia, more than twenty-five coal seams were deposited. In some instances, part of a coal basin was depressed and the remainder was stationary. This is indicated by the partings, which increase in thickness toward the depressed side, until they become thick beds.

Cannel Coal, as intimated above, is of exceptional character. The lenticular, or lens-shaped, patches in which it occurs indicate deposition in ponds, into which little or no sediment was carried. The vegetable remains which were dropped or drifted into such a pond were very thoroughly macerated, destroying almost all traces of structure. The occurrence of fossil fish in cannel coal shows that the water above the mass of plant débris was clear, not filled up with a semi-solid body of peat.

6. *Boghead Coal* is somewhat like cannel, but is a dense brown rock, rich in oil, which has been found in the Carboniferous and

Permian of many parts of the world, in Alaska, Kentucky, Scotland, France, Russia, Brazil, Australia, etc. The mode of origin of this peculiar coal has been the subject of vigorous controversy, but the general consensus is that boghead was formed in fresh-water lakes, or brackish lagoons, by accumulations of Algæ, both of the Blue-Green and colonial Green kinds, which differ very little from existing genera.

Coal has been forming throughout unimaginable lengths of geological time, but not until the Devonian period had land vegetation been so far developed as to render such accumulations possible. With but a single known exception, Devonian coal is in thin, unworkable seams. The exception is in Bear Island in the Arctic Sea, south of Spitzbergen, where coal of Devonian date was mined for some years.

As its name implies, the Carboniferous period was preëminently the time of coal-making, and both in extent and in quality the coal of this period much exceeds that of any other. Carboniferous coal fields are confined to the northern hemisphere and to the temperate and Arctic latitudes; in North America coals of this date are in the East and, principally, in the Middle West, extending but little beyond the Missouri River. In Europe, the coal of Great Britain, France, Belgium, Germany, and Russia is nearly all of Carboniferous date. The coal fields of China, which are believed to be the largest in the world, are largely, if not entirely, Permian.

Permian coal is found in restricted areas of Pennsylvania and West Virginia, in France and Western Germany, and all the coal of the southern hemisphere, in Australia, South Africa, and South America, belongs to the Permian period. Triassic coal is found on a small scale in Virginia, North Carolina, and southern Sweden, and very extensively in peninsular India. Coal of Jurassic date is mined near the Black Hills of South Dakota.

Inferior only to the Carboniferous in extent and thickness of its coal measures is the Upper Cretaceous of the Rocky Mountain region and on both sides of the great uplift, from Texas far into Canada. There is some good coal in the Lower Cretaceous of Alberta, which extends over into Montana, and every subdivision of the Upper Cretaceous is coal-bearing somewhere. Most of the Upper Cretaceous coal is a lignite, but there is considerable bituminous coal also, and in Colorado there is a field of anthracite of this

period. In the Puget Sound region there is coal of Eocene Tertiary date, as is also the workable coal of Alaska, its commercial value being largely due to the metamorphosing effect of igneous intrusions. Cretaceous coal occurs in the northern part of the territory. The immense thickness of the brown coal in Germany and the lignites of the south of France and Switzerland are assigned to the Oligocene and Miocene epochs of the Tertiary period. This list is not at all exhaustive, but it includes the principal known coal fields of the world and it shows that coal making began when land plant life had attained the necessary stage of development and that it has continued, at intervals, till the present day.

7. *Petroleum*, or mineral oil, can hardly be classified as a rock, yet the vast amount and great economic importance of this material require that brief mention be made of it. Petroleum is composed chiefly of a "bewildering variety" of hydrocarbons. "The separation and isolation in a chemically pure state of these substances is most difficult, and in many cases has, up to the present, been found impossible." "The numerous varieties of the four principal classes of hydrocarbons: saturated, unsaturated, aromatic, and naphthenic are found in varying proportions according to the origin of the petroleum." (L. Gurwitsch.) In the United States, which produces 70 per cent of the world's annual supply of petroleum, there are five or more geographical regions in which oil is found in commercial quantities, each characterized by chemical differences. The Appalachian oil field, from western Pennsylvania southward, yields oils which are chiefly composed of paraffins and contain sulphur or nitrogen. The paraffins belong to the methane series, of which the general formula is C_nH_{2n+2}; methane itself, or marsh gas, has the composition CH_4 and is the principal constituent of natural gas. In the mid-continental field, including Ohio, Indiana, Illinois, the oil contains more naphthenes, the name originally given to the hydrocarbons of the polymethylene series and still largely used in connection with petroleum; they have the general formula of C_nH_{2n}. The mid-continental oils also contain a relatively high proportion of sulphur compounds, as much as 1.1 per cent.

Oils of the Gulf region, Oklahoma, Texas, and Louisiana, have naphthenes, paraffins, and acetylenes (C_nH_{2n-2}), and other series, and these are characterized by the presence of free sulphur, which crystallizes out separately. Nearly all petroleums contain nitrogen compounds, up to 1 per cent, the nature of which is not well

understood, but they are especially abundant in California oils, in which they may form as much as 20 per cent. California oils are made up of several of the hydrocarbon series, chiefly of the naphthenes.

The solid hydrocarbons are grouped together under the term *asphalt*, or bitumen, and are found all over the world. Asphalt is apparently formed by evaporation of the more volatile constituents of petroleum and the action of oxygen and sulphur. "Between liquid petroleum and solid asphalt there are numberless intermediate substances. Indeed, there is no distinct break in the continuity of the series from natural gas to bituminous coal." (F. W. Clarke.) Asphalt often saturates sandstones, such as the Green River asphalt of Kentucky, or limestones, such as the Val de Travers rock in Switzerland. Rocks of this description are excellent for paving and road-making, after being finely crushed and then compacted in place by a steam-roller.

The geological date of the formation of a given body of petroleum is by no means always easy to determine, because of the migratory capacity of oil and gas, in consequence of which it may find final lodgment in rock of very different date from that in which it was originally formed. However, something may be determined as to the geological age of the various oil accumulations. The petroleums found in the eastern part of the continent, those of the Appalachian, Canadian, Mid-Continental, and Gulf oil fields, are in Palæozoic rocks, Ordovician, Silurian, and especially Devonian. The oils of the Rocky Mountain field are in Cretaceous rocks and those of California in Miocene Tertiary. The occurrence of petroleum requires porous rocks in which the oil is stored and a covering of impervious rocks to prevent the escape of gas, for it is gas pressure that makes a spouting well, or "gusher." Oil is found almost entirely in rocks of marine origin; coal is a fresh-water product, oil was formed in the sea.

Geographically, petroleum is very widespread, all of the continents, except Africa, having important supplies. In North America, Canada is a small producer, Mexico a very large one. In South America, Venezuela promises to take the second place in oil production; Colombia, Peru, and Argentina are also sources of oil. In Europe, the oil fields are concentrated in the southeast; Roumania, southern Poland and, especially, Russia are large producers. Mesopotamia, Persia, Burma, Japan, and the greater

islands of the Dutch East Indies are the principal Asiatic regions of oil production, and small amounts are obtained in Algeria and Egypt. Like coal, oil is but scantily present in the southern hemisphere, so far as is at present known.

The origin of petroleum is a much-debated problem and divergent views concerning it are still held. Several very eminent chemists have maintained the inorganic formation of the hydrocarbons, and it is true that some volcanic exhalations, igneous rocks, and meteorites do contain such compounds, but they are utterly insignificant in quantity. The conditions under which hydrocarbons are synthesized in the laboratory are such as cannot obtain at or near the surface of the earth. As oil has no organic structure, the proof of its origin is not so simple and direct as in the case of coal, but the geological relations make the organic origin of petroleum much the simplest and most probable solution of the problem. Both plants and animals would seem to be the initial sources of petroleum: "The nitrogen bases of California petroleum furnish perhaps the strongest evidence that the proteids contribute their share to the make-up of petroleum, and show also that these particular oils are of animal origin." The Appalachian oils, on the other hand, are believed to be of vegetable origin. "The association of gas, oil, salt, sulphur, and gypsum, which some writers have taken as evidence of former vulcanism, is much more simply interpreted, both chemically and geologically, as due to the decomposition of organic matter in shallow, highly saline waters near the margin of the sea." (F. W. Clarke.) Organic matter is very widely diffused through the sediments. As Orton has said, "Disseminated petroleum is well-nigh universal; the accumulations are rare."

8. *Oil shales* contain so large a proportion of organic material that, on distillation, they yield mineral oil, but the petroleum does not exist, as such, in the rock. Oil shales of marine origin derive their hydrocarbons largely from fossil fish, which are present in vast multitudes in the rock; those of fresh-water origin are filled with gelatinous algæ. The Green River Shales of Wyoming and the adjoining parts of Colorado and Utah are oil shales laid down in fresh water and saline lakes and their high percentage of hydrocarbons is chiefly derived from algæ, but they also contain great quantities of fossil fish, which doubtless add materially to the organic content.

B. Æolian Rocks

The rocks of this group were formed on dry land and are very much less common and extensive constituents of the earth's crust than are the water-laid or aqueous rocks. Nevertheless, they often have a significance disproportionate to their extent, because of the information they give as to the physical geography of the place and time of their formation.

1. *Blown Sand* is heaped up by the wind into *dunes*, or hills, which travel before prevailing winds, until stopped by some obstacle. Sand dunes are especially characteristic of low-lying, flat coasts and of deserts. The sand-grains, abraded by contact with one another and with hard rocks, are smaller, less angular, and more rounded than the grains of river or even beach sands. Desert sand-grains are pitted and frosted, like ground glass, in a characteristic way.

2. *Drift-sand Rock* (also called *æolian rock*) is the consolidated sand of dunes, forming a rock which is stratified by the wind in an irregular and confused sort of way. If the sand contains any considerable quantity of calcareous matter, such as comminuted shells, the solution and redeposition of this by percolating rain-water binds the loose sand into quite a firm rock. The calcareous sands of Bermuda are an oft-quoted example of this action.

3. *Talus* is a mass of blocks, large and small, which accumulate at the foot of exposed cliffs and other favorable places, due to the riving action of frost, or to the expansion and contraction of rock caused by great changes of temperature. High mountains, above timber-line, are often covered with an incredible quantity of talus, wherever the slopes are not too steep for the loose blocks to lie, and great sheets of it are found in many stony deserts.

4. *Breccia* is a rock composed of angular fragments, much smaller than talus blocks, cemented into a solid mass.

5. *Soil*, except vegetable loam, is the residual product left by the decay or disintegration of rock on land-surfaces. Most soils have been formed in the places where we now find them, but in a relatively few instances, such as alluvial and glacial soils, the material has been transported and deposited far from its place of origin. Surface soil is unstratified and contains more or less organic matter and is more or less filled with the roots of plants. Soils may be buried under deposits made by a river or a transgressing sea, and,

in the latter case, they are interstratified with marine rocks. Ancient soils have often been preserved in this manner: filled with fossil roots and, sometimes, with the stumps of trees still standing in them.

6. *Loess*, a German word, for which there is no English equivalent, is a very fine-grained, terrestrial deposit made by the wind, and is largely dust. It is usually unstratified and has a more or less pronounced vertical cleavage and is so firm that vertical faces remain standing for a long time.

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CHAPTER XI

THE FORMATION OF SEDIMENTARY ROCKS — SURFACE AGENCIES

The first step in the formation of a sedimentary rock is the production of material for it; for, by definition, the rocks of this class are made from the débris of older rocks. Ultimately, this débris must have been derived from igneous rocks, but, in any given instance, the material may have been reworked many times and passed through many cycles of sedimentary accumulations. The dynamic agencies which operate at and near the surface of the earth, save such as are of subterranean origin, like volcanoes, are all manifestations of solar energy, and their work consists in the *destruction* and *reconstruction* of rock and in the wearing away of the land-surface.

The processes of rock destruction and reconstruction are complementary, each involving the other; for, save for the rare radio-active elements, the matter of the earth is practically indestructible and constant in quantity. It is true that meteorites contribute matter continuously to the earth from outer space, but the amount is relatively so small as to be negligible. As far back as geological history can be traced, no evidence of any destruction of the common and abundant elements can be found. The destruction here described is merely the breaking down of rocks and minerals into simpler compounds, and reconstruction cannot go on without it. Ceaseless cycles of change are everywhere in progress, new combinations continually formed and older rocks reworked into newer.

These cycles of change begin with the chemical *decomposition* or mechanical *disintegration* of the minerals of a preëxistent rock, igneous in the first instance. Next follows the *transportation* of the débris, for longer or shorter distances, its *deposition* in a new place and, finally, its *consolidation* into solid rock.

The processes of rock destruction and removal, which are grouped together under the general term *erosion* or *denudation*, are,

for the most part, operative on the land, while those of reconstruction take place principally beneath bodies of water and, above all, on the bottom of the sea. Important work of reconstruction takes place on the land, but its significance is chiefly historical and, quantitatively, is not at all comparable with deposition in the sea. The denuding agents which, if not interrupted, will eventually cut the land down below sea-level, do not act uniformly all over the land surface, as a plane reduces the thickness of a board, but with much greater rapidity along drainage lines.

The work of the surface agencies is profoundly affected by the diastrophic movements of the earth's crust, which bring about the successive geographical cycles. A low-lying region suffers very little loss from the eroding agents, for the driving force in denudation is gravity. In such a region the streams are sluggish and the forces of weathering are reduced to a minimum, so that erosion is very slow. Such a surface may persist for long periods of time without noteworthy change; it is said to have reached *base-level*, a term which will be more fully explained in connection with rivers.

The relief of a given region is due to differential erosion, which, in turn, is determined by the rock-structure and the arrangement of harder and softer masses. In general, the softer masses are removed first, while the harder remain for a much longer time. The most efficient agents of erosion are the atmosphere and the river; the rate and kind of erosion are largely determined by climate and there is, therefore, a climatic control of topography.

All of the surface agents act both destructively and reconstructively, according to circumstances, but with very different degrees of efficiency. Some are eminently destructive, others as eminently reconstructive, while others again are most effective as agents of transportation. Furthermore, the depth below the surface at which the operations are carried on has very important bearing upon the effect produced. We may regard the earth's crust as being made up of a number of concentric shells, of somewhat irregular thickness and indefinite and even fluctuating boundaries. The outermost shell, which extends down to the level of the ground water, is the *shell of weathering* (Van Hise) and is characterized by the hydration, oxidation, and carbonation of minerals, and great quantities of material are dissolved and carried away. As a result, the component minerals of the igneous

rocks are decomposed and the rocks themselves become soft and friable; the newly formed minerals are few in number, of simple composition, and, usually, imperfectly crystallized. The minerals of the sedimentary rocks, being already decomposition products, are not further decomposed by weathering, but more or less of their substance is removed in solution, in consequence of which the rocks so attacked crumble into soil.

The second shell, that of *cementation* (Van Hise), extends downward from the ground-water level to a varying depth, with undetermined lower boundary, and is largely saturated with water, so that the supply of free oxygen and carbon dioxide is limited. While oxidation and carbonation do occur, they are less important than hydration, and the resultant minerals are more crystalline than in the shell of weathering. Some solution is effected, but deposition is more important, and the general effect of the various processes is to increase the hardness of the rocks.

The surface agencies must be classified for the purpose of studying their operation and effects, yet it must always be remembered that classification cannot but be artificial, separating processes that belong together. In nature the various agencies, operating at the same time, balance and modify one another, sometimes with increased and sometimes with lessened efficiency, but generally with some modification of effect. The simplest classification gives six categories of the surface agents: (1) the atmosphere, (2) running water, including the very slow-moving groundwater, (3) ice, (4) lakes, (5) the sea, (6) animals and plants. The work of these various agents is principally mechanical; water is the indispensable agent of chemical change.

THE ATMOSPHERE

A. Destructive Processes

The destructive work of the atmosphere is comprehensively termed *weathering* and is plainly displayed in ancient buildings, or tomb-stones, or the faces of cliffs. Freshly quarried stone has a very different appearance from the same kind of rock that has long been exposed to the weather. Of all the destructive agents, the atmosphere is by far the most effective, because no part of the land-surface is exempt from its attack, and destruction is everywhere and unceasingly going on. The sea-bottom cannot be reached by

the atmosphere and lakes protect their basins against it, but the dry land is universally exposed to its unceasing destructive action. While such agencies as rivers and the sea do work which is much more obvious and striking than that of the atmosphere, yet their work is far more restricted, that of the sea is almost entirely confined to its coast and that of the river to its valley and even in the operations of the river and the sea, atmospheric work is an important auxiliary. Weathering varies greatly in the rapidity of its work in different regions. There are, in the first place, different climates to be considered, differences in the amount and distribution of the rainfall, of temperature and the winds. In the second place, the various kinds of rocks differ greatly in the resistance which they oppose to the work of destruction, owing to differences in hardness and chemical composition. Again, the presence or absence of a covering of protective vegetation greatly modifies the rate at which erosion is effected.

All these varying factors concur in producing very irregular land-surfaces. The overlying screen of soil conceals much of this irregularity, and were that screen removed, the surface of hard rock would be seen to be very much more rugged than is the surface of the soil. When the land has been planed down to a featureless slope, lying but little above the sea, it is said to be *base-leveled* or to have reached the *base-level of erosion.*

The atmospheric agents may be divided into (1) rain, (2) frost, (3) changes of temperature without frost, (4) wind.

I. Rain

Chemical Work. When the gravedigger in *Hamlet* said: "For your water is a sore decayer of your dead body," he uttered a great geological truth, if we may take "dead body" to mean everything that is not alive. Directly, or indirectly, water is the universal solvent and destroying agent. The aim of all construction, whether engineering or architectural, roads or bridges, houses, cathedrals or "skyscrapers," is to exclude water, or, if that is not feasible, to lead it out again as soon as may be.

Of the atmospheric agents, rain is the only one which produces chemical changes, but it also has great mechanical effects. Its work varies greatly, in accordance with climatic factors. The annual precipitation may be the same in two regions, but, in one, the rainfall may be in very frequent, gentle showers and, in the

other, in less frequent, but very violent downpours. In such conditions, the work of the rain will be very different in the two regions. Still another kind of effect is produced when there are regularly alternating wet and dry seasons. Temperature also modifies the work of the rain in important ways, so that results are brought about in warm countries quite different from those of temperate and cold latitudes, and the covering of vegetation has always to be taken into account. Thus, each climatic zone displays the work of rain with characteristic differences. Perfectly pure water would not act powerfully upon rocks, though decomposing their complex minerals by hydrolysis, but such water does not exist in nature. Rain water in its condensation absorbs free oxygen and carbon dioxide and these gases add much to its solvent powers.

While all rocks yield eventually to the action of water, this action is entirely different in the igneous and the sedimentary rocks. Taking up the igneous, we find that one of the first and simplest effects of water is the *hydration* of the minerals, especially the feldspars, which are exposed to it. Hydration, which is the taking of water into chemical union, is an effective agent of decay; it causes an increase of volume and therefore a greatly augmented pressure within the rock. In the District of Columbia, in boring the aqueduct tunnel, granite rocks were found to be "disintegrated to a depth of many feet, with but a loss of 13.46 per cent of their chemical constituents. . . . Natural joint blocks brought up from shafts were, on casual inspection, sound and fresh. It was noted, however, that on exposure to the atmosphere, such not infrequently fell away to the condition of sand." (Merrill.)

The exfoliation of granite, or splitting off of thin sheets from the surface of the rock, has generally been referred to the effects of heating of the mass by the sun's rays, with consequent expansion (see p. 223) followed by chill and contraction at nightfall. Professor Blackwelder has shown, however, that the expansion of the feldspars through hydration is a more important cause of this action. (Blackwelder.)

The effects of *oxidation* are chiefly seen in the iron minerals, whether of igneous or sedimentary rocks, and this action brings about striking color changes, for compounds of iron form the principal coloring matter of rocks and soils. Ferrous compounds give little color, and the rocks in which they occur are apt to have a blue or gray tint, due to other organic or inorganic substances. Such

rocks, when exposed to the action of air and water, have their ferrous compounds oxidized to ferric oxides and ferric hydrates, the former giving a red color, the latter various shades of brown and yellow.

When fired in a kiln, a blue clay will yield red bricks by the conversion of ferrous carbonate ($FeCO_3$) into ferric oxide (Fe_2O_3). In nature, rain-water effects a somewhat similar change and the contrast between the superficial and the deep-seated parts of the same rock is often as great as between red brick and blue clay. Weathered blocks stained red, or, more commonly, a rusty brown on the outside, are often blue, gray, green, or nearly black inside, because the change is an entirely superficial one.

In the disintegration of the igneous rocks, the most important change is the decomposition of the feldspars, the exact chemical nature of which is doubtful. The problems of the decomposition of minerals are largely those of colloids; colloid silica and clay being important products. Orthoclase and microcline, for example, have the composition K_2O, Al_2O_3, 6 SiO_2 and have generally been regarded as double silicates of potassium and aluminium, but they may be salts of alumino-silicic acid and, in that case, are readily decomposed by water (hydrolysis). The potassium and some of the silica are removed in solution and the insoluble residue is clay (Al_2O_3, 2 SiO_2, 2 H_2O). "Many geological writers, especially those of the older school, attribute this process of kaolinization to the action of carbon dioxide dissolved in the ground-water. . . . It is impossible at present to say definitely which of these explanations is the correct one; probably both apply in different cases and the point is of no real importance, as the final residual and insoluble product is the same." (Rastall.)

It often happens that a potash feldspar is converted into the white mica sericite, either by ordinary weathering or by the action of hot waters and vapors of volcanic origin. The chemistry of the change is a matter of debate.

The plagioclase feldspars, of the lime-soda group, have a more variable composition and therefore a more extended range of residual products. Clay, calcite, zoisite ($Ca_2(AlOH)\ Al_2(SiO_4)_3$), a calcium aluminium silicate, and some members of the chlorite group are the commoner residuals.

In most tropical regions, where there is a long dry season, followed by a wet season of violent rainfall, the decay of the feldspars

and other aluminium silicates is characteristically different from what has just been described as occurring in temperate climates.

FIG. 73. — Platy jointing in diabase; above, spheroidal weathering and transition to soil, Rocky Hill, N. J. (Photograph by Sinclair)

These minerals lose not only their alkaline and calcareous constituents, but also the silica, giving as a residue *bauxite*, the hydrated oxide of aluminium. The iron is oxidized, forming

nodules and masses of limonite, often valuable as ores, and stains the bauxite a deep red, forming the characteristic warm-country surface deposit called laterite. As laterite is formed only where there is abundant rain, it has been suggested that it may be due to the action of bacteria (Holland), but the suggestion has not been proved.

FIG. 74. — Cradle Rock, boulders and blocks of weathering of Rocky Hill trap, Province Line Road, N. J.

Igneous rocks frequently weather into masses of rounded boulders, which are often mistaken for glacial moraines. The rounded shape is due to the more rapid decay of the angles and edges of the original joint blocks, which are attacked on both sides at once and are thus removed more quickly than the broad sides of the blocks. When acquired, the rounded shape is long retained, because then decay penetrates at a nearly equal rate from all sides.

White mica, or muscovite, is remarkably stable and yields but

very slowly to decomposition; many sediments contain considerable quantities of mica flakes, which are especially common in micaceous sandstone. Brown mica (biotite) yields much more readily to weathering, but the process is very obscure; sometimes chlorite and potash solutions are the results of decomposition.

The ferro-magnesian minerals, which contain no alumina, give rise, on decomposition, to talc, magnesium and calcium carbonates and iron oxides, the silica being mostly carried off in solution.

FIG. 75. — Exfoliating spheroids in Basalt, Millersdale, England. (Photograph by S. H. Reynolds)

Olivine gives rise to serpentine, and this may be further decomposed to form magnesium carbonate, or magnesite, which is of economic value.

The igneous rocks contain a large number of accessory minerals (p. 54), the presence or absence of which has no effect in classification. Many of these, such as zircon, sphene ($CaTiSiO_5$), magnetite, garnet, and corundum, and a long list of minerals which are found in pegmatite, such as tourmaline, beryl, and topaz, are very resistant to weathering and merely break up into fine particles, which are constituents of sands, but usually in very small proportions. Comminuted ferro-magnesian and accessory minerals are sorted by water to make sand-like masses, but very heavy.

The weathering of igneous rocks thus produces a series of simple and stable minerals, which are the material from which the sedimentary rocks are built up. Clay is much the most abundant of

the materials derived from the decomposition of the igneous rocks and, after that, quartz, which is not changed except in being broken up into smaller fragments. Owing to its hardness, its simplicity and stability of composition, quartz is an abundant and important constituent of all three of the main groups of rocks. The limestones, which are such common and widespread sedimentary rocks, are mostly the accumulations of animals and plants which extract the calcium carbonate from solution, but the lime compounds were originally derived from the igneous rocks. Other substances, which are formed by the decomposition of the igneous rock minerals, may be of economic value, as are serpentine, talc, and magnesite, the iron oxides, but they are too limited in quantity to be of geological importance.

The weathering of the sedimentary rocks is entirely different in its methods and results from that which destroys the igneous. As will be seen, the mechanical agents, wind and frost, disintegrate all classes of rock alike, but the chemical work of water is different because the mineral constituents of the sedimentary rocks are themselves the simple and stable results of decomposition. Except the limestones, the sedimentary rocks are made up of fragments, coarse or fine, of insoluble minerals, held together by some cementing substance; rain dissolves and carries away this cement and the remainder of the rock crumbles into a friable soil. Concrete, when made with gravel, is an artificial conglomerate, and when attacked by a strong acid, which dissolves the cement, the remainder crumbles into sand and pebbles. Usually, concrete is made in the proportions of cement 1, sand 3, gravel 6, and thus 10 per cent of cement suffices to bind the sand and gravel into an artificial stone, which is famous for solidity and strength. The analogy with the disintegration of a sedimentary rock by the solvent action of water is thus complete.

Sandstones are composed of grains of quartz (SiO_2) cemented together; the cementing substance may be silica, some compound of iron, such as Fe_2O_3, or calcium carbonate ($CaCO_3$), and the removal of this cementing substance by solution causes the rock to disintegrate into sand. As atmospheric waters have but little effect upon silica, the disintegration of the siliceous sandstones is extremely slow; underground, the solution is a little more effective. Ferric oxide is unchanged by rain water at the surface, but under the soil it is converted into ferrous carbonate, which is soluble in

water containing carbon dioxide, as all natural waters do. The upper layers of red sandstone are, in the course of time, and sometimes rapidly, converted into layers of loose sand, which is often bleached by the removal of the iron which stained it red. Calcium carbonate is very soluble and sandstones in which the cement is calcareous disintegrate rapidly. In shales which, though usually quite soft, are sometimes very hard, weathering operates in the

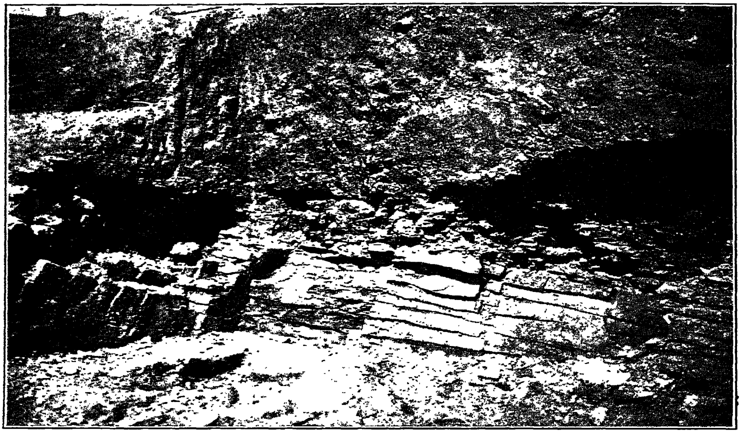

FIG. 76. — Soil forming from decay of Triassic sandstone, Princeton, N. J. (Photograph by Wanless)

same manner, dissolving and carrying away the cement, while the insoluble portion breaks down into mud or clay.

The sandstones, which have a great variety of color, are extensively used as building stones, and their value for such purposes depends principally upon the cementing substance. A calcareous sandstone weathers rapidly, but the ferruginous and siliceous kinds are very durable in a wall exposed freely to the air, whatever their behavior underground.

Limestones are among the few rocks which are chiefly, sometimes almost entirely, made up of soluble material, calcium carbonate, or calcite. This is attacked by rain-water and carried

away in solution, leaving the insoluble impurities, clay or sand, to form a soil. Clay is the most usual impurity, and hence limestone regions generally have clay soils; but sand also occurs, and

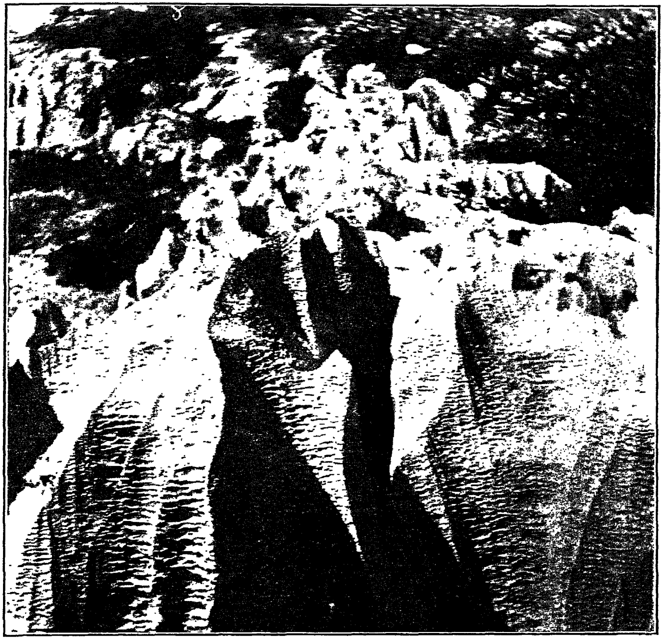

FIG. 77. — Weathered Triassic limestone, Shasta Co., Calif. (Photograph by Stanton, U. S. G. S.)

when the sand forms a coherent, but porous and spongy-looking mass, it is called *rotten stone*.

Soil is the product of the disintegration or chemical decomposition of rocks and, for the most part, originated where it is now found, lying upon the parent rocks. Some soils are largely decayed vegetable matter and others have been transported longer or

shorter distances, such as *alluvial soil*, a river deposit, and *glacial soil*, transported by ice, but these also were originally derived from rock decay. The gradual transition of rock to soil may be observed in shallow excavations, such as railroad cuts, quarries, wells, cellars, etc. In *pluvial* climates, or those of large rainfall, such as the eastern half of the United States and Canada, there is a distinct demarcation of topsoil, near the surface of the ground, and *subsoil* below. Save in sandy areas, the topsoil is dark colored, due partly to the admixture of vegetable mould, partly to the complete oxidation and hydration of its minerals, and is unstratified. Next follows the *subsoil*, which, owing to the absence of vegetable matter and to less complete oxidation and hydration, is of a lighter color and often shows stratification, if derived from a sedimentary rock. Fragments of the parent rock, which have resisted disintegration, are often embedded in the subsoil, which grades downward imperceptibly into *rotten rock* (not to be confused with rotten stone). Rotten rock appears to be sound and unchanged, but is friable and crumbles in the hand, and from this to the solid unaltered rock the passage is very gradual.

Topsoil and subsoil have been traversed innumerable times by descending rain-water, and soluble constituents have, to a large extent, been leached out of them, but, happily, the soil has the unexplained property of retaining the soluble compounds of potash, phosphoric acid, and other substances essential to plant life, though even of these some part is leached out. In arid regions, where rain plays a much smaller part in the production of soil, there is no distinct demarcation between topsoil and subsoil. The leaching has been much less effective than in moist regions, and nearly all the plant-food has been retained. This explains the incredible fertility of desert soils when irrigated.

In the Northern States, below the glaciated regions, the soil is of very variable but moderate depths, and this depth increases southward, for the processes of rock-decay are accelerated by higher temperatures. In the Southern States the feldspathic rocks are often thoroughly disintegrated to depths of 50 to 100 feet. In the Tropics of heavy rainfall, the soil is often 200 to 300 feet in depth; it is this heavy mantle of soil and the dense cover of vegetation which make geological work so very difficult in the wet Tropics.

Mechanical Work. The mechanical work of rain is comprehensively covered by the term *rain-wash*, and under ordinary con-

ditions in pluvial climates it consists in carrying the loose soil down from higher to lower levels. Even in countries well covered with vegetation, the streams which are ordinarily clear become turbid and muddy after heavy rains, because of the soil which the rains and rivers that flow through alluvial valleys or plains, like the Missouri and the lower Mississippi, are always scouring. Other factors being equal, the rapidity with which the rain washes down the soil is determined by the steepness of the slopes, for gravity is the force at work. On cliffs and steep hillsides, the soil is removed as fast as it is formed and in such places is very thin, or altogether lacking, exposing the bare rock, while in the valleys it accumulates, often to great depths. Even on gentle slopes, the rains slowly move it downward to the streams, which eventually carry it to the sea. Thus, the soil is not stationary, but is slowly moving seaward under the impulsion of rain and rivers. Aside from soils transported by rivers, glaciers, or the wind, the soil of any area is a residual product and its quantity represents the surplus of chemical decomposition over mechanical removal.

Rain wash is greatly increased by extreme violence of precipitation; a single "cloud burst" will do far more damage than the same amount of rain falling in gentle showers. Those who know only temperate climates can form but very imperfect conceptions of the tremendous violence of tropical rains. In northern India, for example, the foothills of the Himalayas receive a precipitation of more than forty feet (!) in the six months of the wet season; especially remarkable is the quantity that often falls in a single day. Sir Charles Lyell says of these hills: "The channel of every torrent and stream is swollen at this season and much sandstone and other rocks are reduced to sand and gravel by the flooded streams. So great is the superficial waste, that what would otherwise be a rich and luxuriantly wooded region is converted into a wild and barren moorland."

The action of rain, chemical and mechanical, upon the rocks is thus exceedingly varied, so many and so different are the factors involved. Marked differences occur in adjacent regions and even in the same continuous body of rock. One of the most remarkable monuments of rain erosion is exhibited in the curious regions of the far Western States known as the *bad lands*, a term derived from the French "mauvaises terres à traverser." These cover many thousands of square miles in the Dakotas, Nebraska, Wyoming, Utah,

New Mexico, etc., all, it will be noted, in the arid and semi-arid parts of the country. The rocks are nearly horizontal beds of soft sandstones and indurated clays which break down rapidly when wet. The rainfall is light, but made effective by the lack of protecting vegetation. At the present time, the action of the rain is ordinarily very slow, because the soil which covers the "buttes" becomes almost waterproof when wet, and sheds the rain like a tin roof, but where the bare rock is exposed, the disintegration proceeds very fast and often the destruction wrought in a single year is quite astonishing. The different strata resist

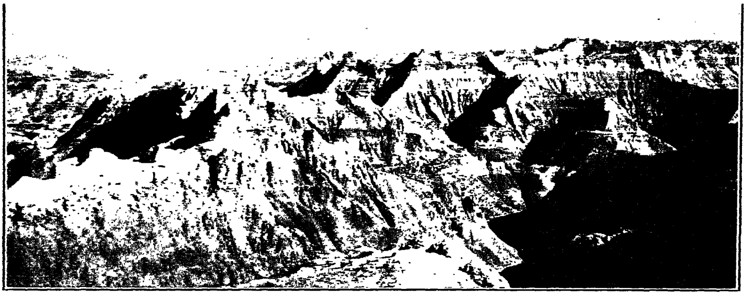

Fig. 78. — White River Bad Lands, S. D. (Photograph by Sinclair)

disintegration in varying degrees, and even in the same bed some parts are much more durable than others. This differential weathering has resulted in that remarkable variety and grotesqueness of form, resembling the ruins of gigantic towers and castles, for which bad-land scenery is famous. A variant of this topography is seen in the rain columns of the Dolores River, Colorado (Fig. 79), where each column, carved out of a once continuous body of soft sandstone, owes its preservation to the capping of a thin slab of harder rock. Similar columns, near Bozen, in the Tyrol, are in process of carving from a boulder-clay, the boulders protecting the column below.

The mechanical wash of rain is greatly retarded by a covering of dense vegetation, especially of grass, stems, and roots, which form an elastic mat that protects the soil against the impact of rain-drops and the wash of rain-rills. The contrast between a

dirt road and the adjoining grass fields after a torrential shower is often very striking. The road is torn and gullied to the depth of several feet, the fields are quite unaffected. It is for this reason that cuttings through soil, or embankments built of it, are

FIG. 79. — Pillars of erosion, Dolores River, Col. (U. S. G. S.)

sodded, to protect them against the assault of the rain. A remarkable instance of this protection is given by the divide between the White and Cheyenne rivers in South Dakota. This is a rolling upland, covered with grass and looking like any other part of the Great Plains, but as one proceeds northwards and reaches the edge of the table, a most wonderful view of the "Big Bad Lands" opens before him, which seem to belong to some other world. The rocks are the same in both areas, but in one the rain has prevailed, the grass in the other.

Forests exert a similar protective effect, and their removal, especially on mountain slopes, is often followed by disastrous results. Speaking of the soil destruction in the old fields of southern Mississippi, the late W J McGee said that the soil is washed away, "leaving mazes of pinnacles divided by a complex network of runnels glaring red toward the sun and sky in strong contrast to the rich verdure of the hillsides never deforested. . . . Whole villages, once the home of wealth and luxury, are being swept away at the rate of acres for each year." The U. S. Bureau of Forestry, in endeavoring to check this wanton and irreparable waste, deserves the support of every citizen.

II. Frost

As here employed, the term *frost* is given the technical meaning of freezing water, not merely the temperature of 32° F. (0° C.). Water behaves in a very exceptional manner on solidification; when chilled, it contracts and becomes more dense down to a temperature of 39° F. (4° C.), when it attains maximum density. Chilled beyond that point, it dilates to the freezing point, when it suddenly expands by about one-eleventh of its bulk and with tremendous force. This property of water is a very fortunate one for living things; owing to it, freezing begins at the surface, not at the bottom, and so streams and ponds do not freeze solid, but are covered with a sheet of ice, which increases in thickness so long as freezing temperature continues without a thaw. As ice is less dense than water, it necessarily floats, which is merely another way of saying that water expands on freezing. The pressure exerted by solidifying water increases as the temperature is lowered, reaching a theoretical maximum at − 8° F. (− 22° C.), when it rises to nearly 34,000 pounds per square inch. Thick iron pipes are burst like paper tubes and most people who live in coun-

tries with cold winters know the trouble caused by bursting water pipes.

All consolidated rocks are divided by *joints* into masses of blocks of greater or less size, and the blocks, in turn, have flaws and rifts down to those of microscopic size. All these clefts and crevices are filled with water, at least in pluvial climates, as may be seen on examining freshly quarried stone. When exposed in a bare cliff or mountain peak to a low temperature, the water freezes, expanding

FIG. 80. — Block of Granodiorite, shattered by frost and insolation, Pack Saddle Mountain, Ida. (Photograph by E. Sampson, U. S. G. S.)

with tremendous power, and forces the joint blocks off the exposed face of the rock. At the foot of every cliff, in climates with cold winters, there is a mass of such blocks, called *talus*, and in the high mountains, above timber-line, incredible masses of frost-made talus accumulate on every slope, which is not too steep for the blocks to rest. At the foot of the rocky cliffs at the Delaware Water Gap, or along the Palisades of the Hudson, the talus extends up for half or two-thirds the height of the cliff and is being continually added to.

The same shattering process goes on, breaking up the blocks into smaller and smaller pieces, how small those pieces may be is determined by the character of the rock. In plutonic igneous rocks, which have several different mineral components, each

with its own rate of contraction, the crystals tend to pull asunder when expanded by heat or contracted by cold, and this, in addition to the riving action of water freezing in minute crevices, causes the rock to break up into pieces only a fraction of an inch in diameter, like an angular gravel. For this there is no specific English word, but we may use the German term *Grus*. At Sherman, Wyoming, where the Union Pacific Railway formerly crossed the continental divide, the country, for miles around, is deeply

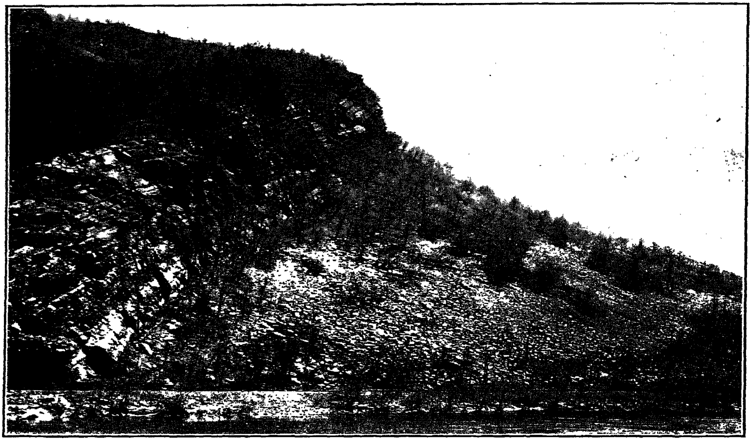

FIG. 81.— Cliff and Talus-slope, Delaware Water Gap, N. J.

buried in masses of finely shattered granite, each piece sharply angular, its crystals with fresh and shining faces, showing no sign of chemical decomposition. Grus makes an excellent ballast for the tracks, and the railway company uses it very extensively for this purpose.

In masses of talus frost causes a downward *creep*, the blocks not remaining indefinitely where they first fell. The talus itself holds more or less water and each freezing causes the blocks to rise slightly at right angles to the slope and each thawing produces a reverse movement, the balanced blocks moving downward at

each thaw, for alternate freezing and thawing are essential to frost action.

Frost is a very superficial agent and is prevented by a covering of a few feet of soil. In polar lands frost penetrates to a depth of several hundred feet, but, as the summer thawing affects only two feet or so below the surface, the freezing below this level has taken

FIG. 82. — Frost Creep or vertical beds of shale, cut of Schuylkill Valley R. R., Penn. (Photograph by Hardin, U. S. G. S.)

place once for all and produces no further effect. Nevertheless, frost is the most effective of the destructive agents in the polar regions, the necessary thawing being accomplished by the direct rays of the sun in summer. In Spitsbergen Beechy found that in summer the mountain slopes absorb quantities of water, which freezes in the winter with very destructive effect. "Masses of rock were, in consequence, repeatedly detached from the hills,

accompanied by a loud report and, falling from a great height, were shattered to fragments at the base of the mountain, there to undergo more rapid disintegration." Similar observations have been made in the Aleutian Islands.

Many passes in the Alps are dangerous in winter, except in the early morning before the sun has had time to melt the superficial ice and allow the blocks which have been forced out during the night's freezing to fall. In the lowlands of warm climates frost is quite ineffective, but, even in the tropics, high mountains are rapidly attacked by frost action, because, above the limit of trees, the rock is exposed without protection to its action.

The action of frost is purely mechanical and produces no chemical change; the smallest fragments of frost-riven rock are sharply angular and the minerals have unaltered and shining faces. But, on the other hand, frost prepares the way for the more rapid action of water, the destructive effect of which is confined to the surface of the rocks and the walls of the fissures and crevices which run through them. By breaking up the rocks the surface exposed to the work of water is greatly increased; for example, a cubic foot of stone, when broken into inch cubes, has its surface multiplied by twelve, thus greatly facilitating the action of water in solution and hydrolysis.

The work of rain and frost are activities of water and are therefore most important in pluvial climates, though abundant rainfall, to some extent, retards its own geological work by causing a thick growth of protective vegetation. Very few regions of the earth's surface are entirely rainless, but nearly all of the continents have great deserts in which atmospheric precipitation is extremely small, but even in these the disintegration of rocks goes through the operation of other agents, though the action is much slower than that of pluvial climate. Even in deserts the occasional rains accomplish something, and they are effectively assisted by two agents which are especially characteristic of arid climates; these are the rapid changes of temperature, which do not involve freezing water, and the wind.

III. Changes of Temperature

In regions of moist or equable climate, changes of temperature are of minor importance and act chiefly in producing crevices, which give passage to percolating waters. In arid regions, espe-

cially on high mountains and plateaus, where great areas of bare rock are exposed and where the temperature-difference between day and night is very great, these changes are much more important. During the day, such rocks as are exposed to the full blaze of the sun are highly heated, so that it is painful to touch them. So far as the heat penetrates, the rock must expand and, after nightfall, when an immediate drop in temperature begins, the outer portions of the rock are cooled and attempt to contract upon the still heated and expanded interior. In arid regions, the

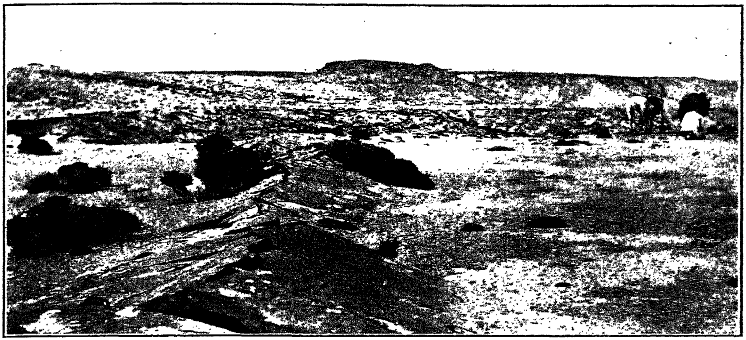

FIG. 83. — Buckle in sandstone due to sun's heat. (Photograph by E. E. Smith, U. S. G. S.)

thin, dry air permits a very rapid chilling by radiation, and often there is a difference of 60° to 80° F. between day and night. Thus, stresses are set up within the rock, to which it must eventually yield and pieces "spawl off" from the surface. The work differs from that of the frost, the latter riving the blocks into smaller and smaller pieces, the former splitting off fragments from the surface. Even when no surface spawling takes place, the crevices and fissures of the rock are slowly widened.

The desert mountains and basins of Central Asia offer remarkable illustrations of the destructive action of the sun upon rocks. In speaking of Turkestan, R. W. Pumpelly says: "Nowhere is there a more desolate land. It is a desert of unexpected forms, time-crumbled mountains and wind-worn cliffs, strange hollow

and pitted boulders and sand-polished stones, efflorescent salt-plains and drifting dunes. . . . Limestone boulders dropped on the plain by floating ice, when the lake stood higher and glaciers came far down, have cracked in the sun and crumbled to conical piles, while whole mountains of the same rock stand shrouded in their own remains. Perhaps the most remarkable instance of desert disintegration is found in the granite mountains ranging on the east. There whole mountains are fast crumbling to arkose and sand, from which some few honey-combed slabs project as pitted, wind-worn ridges. Such are the features wrought by an arid sun and shade with a range of 80° F. from day to night." (*Per contra*, see Blackwelder.)

In the case of coarse-grained igneous rocks, each constituent mineral has its different coefficient of expansion and, when heated or chilled, tends to pull away from the others. For this reason, granite structures do not resist fire very well, but crumble under a moderate heat. In the desert the same occurs, but incomparably more slowly. The writer of these lines once picked up a small piece of granite at Ghizeh, evidently a fragment of the casing of the Third Pyramid; when compressed in the hand, the granite broke down into *grus*, the feldspar crystals keeping their glistening faces and showing no sign of decomposition or hydration.

The effects of insolation are even more superficial than those of frost; a thin covering of soil suffices to protect the rock from overheating and, even where fully exposed, the sun's heat can penetrate but a short distance into the rock.

A somewhat similar rending effect is produced by the crystallization of various salts of calcium and magnesium, which forms crusts and efflorescences in arid regions. These are effects of water, indirectly, yet are almost confined to the desert, and Passarge lists them with frost and insolation as destructive agents.

IV. Wind

Wind is air in motion and is produced by differences of barometric pressure, the air flowing from an area of high pressure to one of low pressure, just as water flows down hill, and the greater the difference of pressure, the greater the velocity of the wind. Observers of the high Alps are of the opinion that the wind, blowing with very great velocity against knife-edges and thin crests

of rock, does actually break them down, an effect which would be quite incredible were it not that the rocks are masses of blocks.

The principal destructive work of the wind is effected on loose materials; small stones and gravel are pushed along the ground, sand is raised and carried along, and a sandstorm in the desert is an experience greatly dreaded by travelers. The sand is ordinarily not raised to great heights, nor carried very far at once, but prevailing winds may drift it for long distances. Fine dust, on the other hand, may be carried for hundreds of miles before being

FIG. 84. — Looking Glass Rock, southwest of LaSalle Mountains, Col., showing wind erosion. Note the two human figures in the opening. (Photograph by Cross, U. S. G. S.)

dropped. All these hard particles, set in rapid motion by strong winds, form a natural sand-blast, which cuts and carves the rock against which the sand is hurled. Artificially, the same contrivance is used: a jet of air, driven at high velocity, carries sand with it which will carve and polish granite, glass, etc., against which it is directed. In pluvial climates, wind-driven sand is effective only on sandy coasts, because, elsewhere, the soil is protected by vegetation, and on such coasts the abrading effects of flying sand are chiefly displayed against buildings, glass windows, etc., for there is little or no rock exposed. On the dunes of almost any inhabited sandy coast, one may find fragments of glass worn to the thinness of paper and with beautifully frosted surface.

In the desert, where naked rocks abound and, usually, sand is present, the high winds set quantities of sand and gravel in motion, hurling it against the rocks and thus cutting them away. As the bulk of this abrasive material and the more effective part of it is lifted only a few feet above the ground, there is much undercutting, producing tables, mushroom, and other fantastic shapes, made more bizarre by the etching work of the sand, which cuts out the softer parts of the rocks and leaves the harder parts in relief. The fine material is thus continually added to by the waste

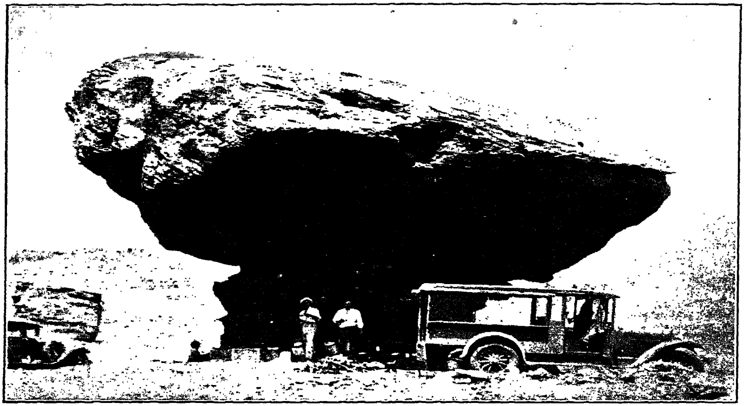

FIG. 85. — Pillar of shale protected from erosion by fallen block of sandstone, near Lee's Ferry, Ariz. (Photograph by H. S. Colton)

of the rocks, and the sand grains, by mutual attrition, are worn, pitted, and frosted, and diminished in size.

Desert pebbles, shaped by the sand-blast, have characteristic forms, often with angulated, faceted, instead of rounded, form. (German, *Dreikanter*.) When of hard, homogeneous material, such as chalcedony, or quartz, they are highly polished; those carved from igneous rocks have the softer minerals cut out and limestone pebbles are cut into beautiful arabesques. Pebbles and larger stones are frequently covered with a film of the black oxide of manganese, derived by solution and redeposition from the

FIG. 86. — Rocks undercut by weathering, Andes of Peru. (Gift of Professor B. Willis)

interior of the rock, and when polished by the sand blast, show the characteristic *desert varnish.*

The destructive work of temperature changes and of the wind is very slow, but it keeps up the circulation of matter in the dryest deserts, and the winds, blowing in some prevailing direction, transport great quantities of sand and dust, sometimes into the sea, or a lake, sometimes into rivers, or, again, to moister regions where it comes under the influence of the rain.

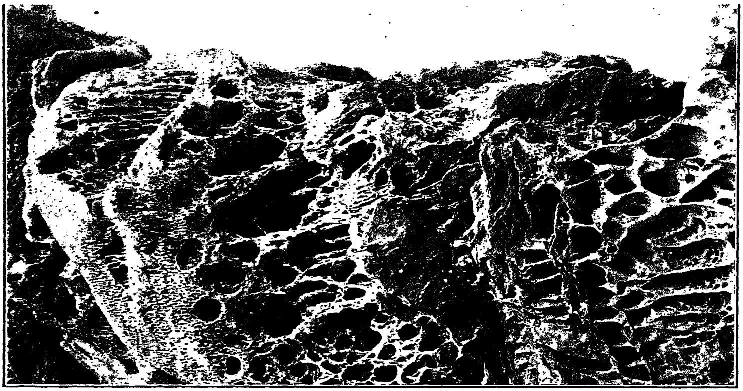

FIG. 87. — Weathered carboniferous sandstone, near Livingston, Mont. (Photograph by Walcott, U. S. G. S.)

B. ATMOSPHERIC DEPOSITION

It will be convenient to make some preliminary statements concerning deposition in general, before considering the peculiarities of atmospheric deposits.

While the atmosphere is the preëminently effective agent of destruction, because the land-surface is always and everywhere subject to it, it also accomplishes some transportation and deposition. In the study of sedimentary deposits, it is usual to make two primary groups, (1) *Continental,* such deposits as are made on land, or in bodies of water not connected with the sea, and

(2) *Marine*, deposits laid down in the sea. Not all deposits are strictly referable to one or other of these groups, for some, like those laid down in estuaries or in almost closed seas, such as the Baltic, are intermediate in character, but these are relatively unimportant in quantity.

1. Stratification. It is characteristic of sedimentary accumulations, whether modern deposits or ancient rocks, that they are *stratified*, that is, divided into more or less parallel layers or beds. The terms *sedimentary* and *stratified* are synonomous. Stratification is produced by the sorting power of water or wind, and that, in turn, is due to the relation between the transporting power and the velocity of a current of air or water. So long as conditions remain unchanged, solid fragments or particles of the same size and specific gravity are thrown down at the same spot. If gravel, sand, mud, and clay are shaken together in a jar of water and then allowed to stand, the various materials will settle on the bottom in accordance with the weight and size of the particles, the coarsest coming down first, the finest last. Yet there is no definite stratification, for the change from one kind of material to another is so gradual that no distinct layers are produced.

Layers clearly demarcated from one another may be formed in either of two ways: (1) by such a change of conditions that the material deposited changes abruptly, though, perhaps, as a mere film of a different substance, or (2) by a pause in deposition, however brief. In the latter case each layer represents a time of deposition, ended by an interval which allows the surface particles to arrange themselves somewhat differently from the attitude which they would take were the deposition continuous. A trench cut through the accumulations of snow in a winter without thaws shows the thickness of each fall. Sometimes a crust was formed on the surface of one snowfall before the next one was deposited upon it. Sometimes a film of dust was brought by the wind in the interval between snow-storms and, again, the surface flakes were so arranged by wind and gravity that the next fall indicated a slight but distinct change.

The planes of contact between the successive layers of sediment are called the *bedding*, or *stratification planes*, and each one of these planes was for a time the surface of the lithosphere, either as a land surface or, very much more commonly, the bottom of some body of water. The thickness of each layer indicates the

length of time during which deposition went on uninterruptedly, and varies from hundreds of feet to the minute fraction of an inch. If the layers are seasonal, recurring annually, they are called *varves*. A very thin layer is called a *lamina*, and in laminated shales these may be thirty to forty to the inch, looking like so many sheets of stout paper.

The transporting power of ordinary winds is much less than that of water, and the particles of wind-borne débris are, in general,

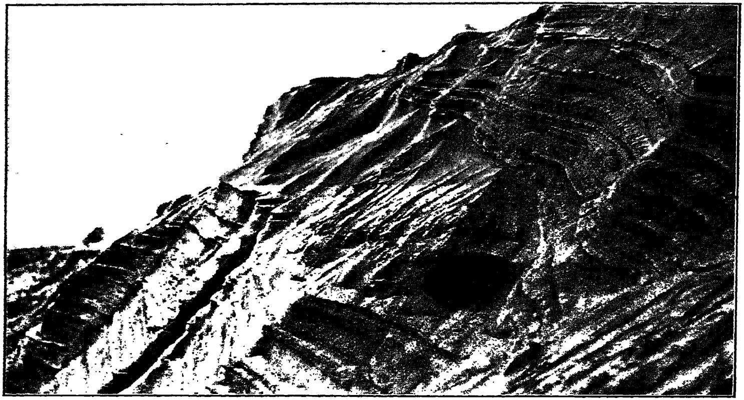

FIG. 88. — Wind stratification in drift-sand, Dune Park, Ind. The round, dark object is a golf cap. (Photograph by Bastin, U. S. G. S.)

much finer than those carried by currents of water. The winds also are less constant in direction and subject to greater and more sudden changes in velocity. As a result, the stratification due to wind is ordinarily much more irregular and confused than that made by water, the beds inclining in several directions. However, wind-made deposits are stratified, and the layers are sometimes so perfectly regular as hardly to be distinguishable from those laid down in water. Fine volcanic ash is often spread over immense areas by the wind and deposited in remarkably even beds or strata.

The sorting power of water, or wind, results in the concentration of similar material, similar in degree of coarseness, or fineness, in

specific gravity and in mineralogical composition. Each bed is thus, as a rule, made up of some predominant substance, gravel, sand, mud, calcareous matter, etc., in a state of greater or less purity. Heterogeneous material is thus separated into its constituent parts, though the separation is seldom quite complete and sometimes it is very imperfect. In a thick series of deposits the materials usually change both vertically and horizontally. Vertical changes of material imply changes of conditions, in accordance with which different kinds of material are successively laid down over the same area. Thus, sand is deposited on gravel, mud on sand, or on calcareous material, or *vice versa*, for there is no fixed order of succession. Such changes are usually abrupt, each bed or layer being sharply demarcated from the one above and the one below it, but in the horizontal direction the changes are gradual and a layer of sandstone may pass by imperceptible gradations into a clay shale and that again into a limestone.

2. Residual Accumulations; Soil. Aside from the relatively small amounts of transported soil, alluvial, glacial, loess, etc., soil originates in place from the decomposition or disintegration of the underlying rock. Few examples of ancient soils are found among the consolidated rocks of sedimentary origin, but such as do occur are of great historical interest: *Laterite* is a tropical soil, characterized by the presence of a large proportion of aluminium oxide, and of a deep red color from the hæmatite, which form lumps and nodules as well as coloring the whole. The soil, as has been shown, is subject to a slow creep down from the hillsides into the valleys and from these into streams which eventually carry it into the sea.

3. Chemical Deposits. In tropical regions, which have regularly alternating rainy and dry seasons, and in arid regions, where the rain falls in torrential showers, followed by long periods of drought, the movement of rain-water through the soil is frequently reversed in direction. During the rains, the soil is saturated with water, which moves downward; in the dry season, evaporation from the surface and capillary attraction cause the water to rise through the soil, carrying various substances in solution, which are deposited on or near the surface. In arid countries, the surface is often white from these deposited materials; salt, soda, borax, calcium carbonate and sulphate are the commonest of these. The iron nodules in laterite are produced in this manner, and, sometimes, these nodules are cemented into sheets of crude hæmatite. Where

the soil and underlying rocks contain quantities of calcium carbonate, the ascending water dissolves and redeposits it on the surface. In South Africa very extensive sheets of hard limestone have been formed in this way. These terrestrial chemical deposits may form over very wide areas, but never in any great thickness.

4. **Mechanical Deposits** are much the most extensive of those formed by atmospheric agency.

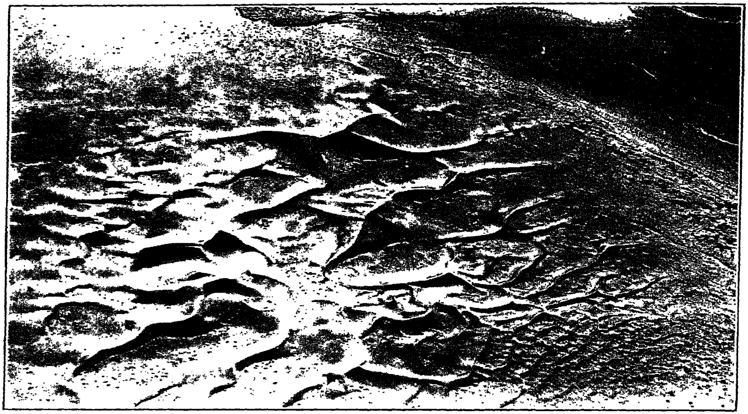

FIG. 89. — Sand dunes on floor of Death Valley, Calif., from height of 10,000 feet. (Courtesy, Chief of Air Corps, U. S. Army)

1. *Talus.* Frost action in all exposed rocks in high mountains and in countries with cold winters causes the accumulation of great masses of talus.

2. *Blown Sand* is piled up by the wind into dunes wherever a sandy soil, or beach, is unprotected by vegetation. The dunes are irregularly stratified and if they contain sufficient calcareous material, will be bound into a firm *drift-sand rock,* or *æolian rock.*

3. *Loess.* Great quantities of fine dust are carried by the wind from deserts and deposited where the wind dies down. If the deposit is unprotected, it will be carried away in its turn, until it reaches a vegetated region, where grass and bushes hold it. In Central Asia the sun is often darkened for days at a time by dust-

storms, and when the storm has died down, a fine deposit of yellow dust is found over everything. Such accumulations of wind-borne dust are called loess, and mantle the drier plains of nearly all the continents. Of the more recently formed loess, the largest accumulations are those of northern China, where it covers an immense area to depths of 1,000 to 1,500 feet, evidently derived from the deserts of Central Asia. The loess has no apparent stratification, but cleaves vertically, giving to the valleys excavated in it very

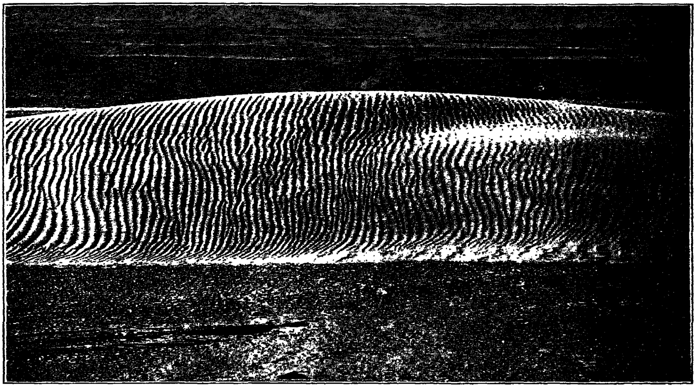

Fig. 90. — Sand dune with wind-ripples, river terraces in distance, Biggs, Ore. (U. S. G. S.)

abrupt sides; the roadways not protected by vegetation are swept out by the wind and cut down into gorges with vertical sides.

Nearly all the continents have desert basins, out of which no water flows, such as the Great Basin of the western United States, which covers nearly all of Nevada and most of Utah. In Central Asia a succession of desert basins, encircled and isolated by mountain ranges, take up a vast area of the continent. The surrounding mountains are undergoing a relatively rapid degradation from the action of frost and of the intense desert sun, and the débris is washed downward by melting snows and transported by the wind. Thus the basins are being filled by the destructive and depositing work of the atmospheric agents, to a depth of many thousands of feet.

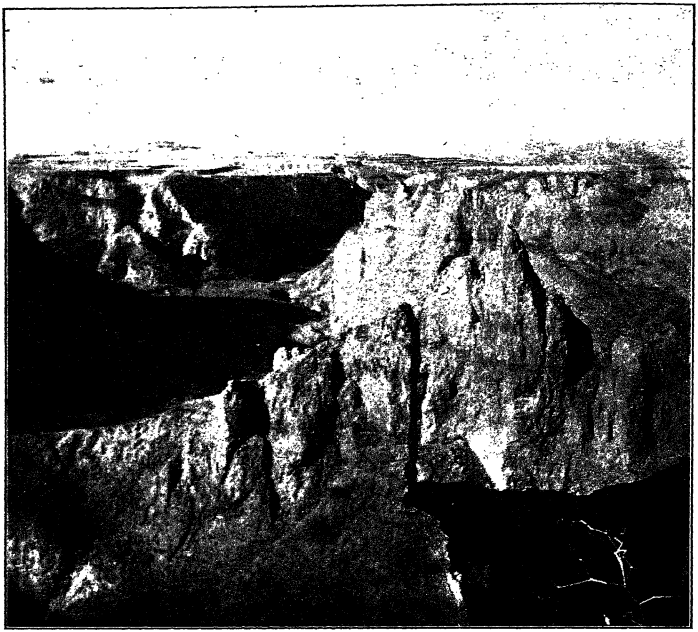

FIG. 91. — Loess deposits, North China. (Photograph by Bailey Willis)

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CHAPTER XII

GROUND WATER AND SPRINGS

Very much the larger part of the water which circulates upon and underneath the land, called *vadose* (shallow) or meteoric, is derived from the atmosphere as rain or snow. As the recent study of geysers has shown, there is strong reason to believe that a certain amount of surface water is of magmatic origin. Whatever may have been true of the earlier ages of the earth's history, at present the relative amount of magmatic, or *juvenile*, water reaching the surface is so small that it may be neglected in any general review of the subject.

The atmospheric precipitation, in the manifold forms of water and ice in pluvial climates, may be divided into three parts. Of these, one part is speedily returned to the air by evaporation, the second part flows over the surface to the nearest stream, and the third part sinks into the ground to a greater or less depth, where it becomes the *ground water*. Some of the ground water is returned to the surface by means of springs, yet a great part of it must reach the sea by subterranean channels. The surface flow, together with the water from springs, constitutes the *run-off*.

The relative proportions of these three fractions of the total precipitation upon the land vary greatly in accordance with climate and topography. In a moist climate with heavy rainfall, the run-off may amount to one-half of the precipitation, for the loss by evaporation is at a minimum. In arid regions, where precipitation is small and evaporation very great, the run-off may be only one-fifth, while the inclosed desert basins and the areas below sea-level have no run-off at all. In similar climates, run-off increases with the steepness of the slopes and is thus proportionately greater in small basins than in large ones.

A. The Ground Water

Beneath the surface and at a depth which varies greatly at different times and places, the soil and rocks are saturated with

water which is called the *ground water*. Near the sea, or lakes, the ground water level, or *water table*, may be but very little below the surface and wells of only a few feet in depth may tap an unfailing supply, while in arid regions, with irregular topography, it may sink to great depths. In the eastern United States the ground water

FIG. 92.—St. Joseph's Well, a sink hole filled with ground water, Clarke Co., Kans. (Photograph by W. D. Johnson, U. S. G. S.)

level stands at depths of 1 to 100 feet, though, owing to special circumstances, there are places where wells must be sunk to several hundred feet to secure any considerable supply of water. In the limestone plateau of eastern Kentucky and Tennessee the ground water is 200 to 300 feet below the surface and is determined by the *drainage level* of the region, that is, the level at which the surface streams flow. In northern Arizona, near the Cañon of the Colorado River, the ground water is 3,500 feet below the

surface of the high plateau and the water supply for the hotels must be brought in tank cars on the railroad.

The ground water table is thus highly irregular and depends upon the amount of precipitation and topographical features. As a general rule, the ground water level in a given area is that of the streams and rises toward the watersheds, or divides, but less steeply than the surface of the ground. The water table also fluctuates with rainfall, rising in wet seasons and sinking in dry, as is shown by the failure of wells and springs in long droughts. The ground water is frequently regarded as everywhere penetrating to great depths in the earth and, from this point of view, "the universal sea of ground water" is described, but there is much reason for believing that this is a mistaken view. In many parts of the world very deep mining shafts encounter water only in the upper levels, and below 2,500 to 3,000 feet the mines are dry and dusty, unless the deep workings intersect fissures in the rocks, when large volumes of water may be encountered. Large fissures cannot, however, remain open to very great depths, because they are closed by rock-pressure. The character and larger structures of the rocks themselves have great effect in determining the depth to which water may penetrate, some rocks being porous and with frequent and open joints, permitting a free passage of water, while others are all but impervious. In the coastal plain of New Jersey, where so many deep wells have been driven, several water-bearing beds have been encountered at different depths, with relatively dry and impervious beds between. Owing to the great mass of porous beds and their arrangement, water penetrates to depths of several thousand feet in the Coastal Plain.

"It is probable that the universal presence of ground water is characteristic of a comparatively shallow surface belt, below which the water which has not been again drawn off at a lower level, or has not been used up in hydration processes, is concentrated into the larger fissures." (Spurr.)

Aside from the extremely slow movement of water through the mass of a porous rock, underground waters follow the larger openings, such as bedding planes and joint cracks. The inclination of the strata, the alternation of porous and impervious beds, the number and capacity of joints and fissures, are the factors that determine the direction of underground flow, which is often directly opposite to that of the surface flow. It frequently

happens that the beds of stratified rock dip into a hill, and thus, on the surface, water flows down hill, underground it flows into the hill, in both instances under the influence of gravity. In all questions of water supply and drainage, it is most important to determine the direction of movement of underground water, in order to avoid sewage contamination and consequent infection.

Save in open caverns, the movement of underground water is excessively slow, sometimes not more than a mile a year, and therefore can accomplish nothing in the way of mechanical abrasion, which is the most important destructive work done by surface streams, but exerts a solvent and decomposing effect upon the walls of the crevices and joint-planes down which the water makes its way. This has already been described in connection with the rain, and the separation of water into the two categories is an arbitrary one. In the shell of weathering, percolating waters are the great agents of dissolving and decomposing the rocks and, therefore, always contain more or less mineral matter in solution, the nature and amount of which depend upon the composition of the rocks which the water has traversed. Below the water table, in the shell of cementation, the water has more reconstructive than destructive effects, though solution and alteration of minerals continue at these lower levels, though not to indefinite depths.

Limestone is the only common rock that is entirely soluble in water containing CO_2 in solution, as all natural waters do. In the shell of weathering, percolating waters dissolve pipes and sinkholes down through a surface limestone and in regions of steep slopes and heavy rainfall, which washes away the soil; extremely rugged, waterless areas of bare rock are produced from limestone by solution. Such an area is called a *Karst* in German (see Fig. 93), a word for which there is no English term. Within the body of the limestone, caves are made by the solvent action of the carbonated water and may extend for many miles, as do the Mammoth Cave of Kentucky and the Carlsbad Caves of New Mexico. Many caverns have considerable streams flowing through them, others are dry, save for a limited drip. Caves and caverns are always in limestone and are due to solution, and while they may extend horizontally to an indefinite distance, their downward extension is limited by the drainage level of the region, for, to produce important effects of solution, water must be in motion,

however slow; stagnant water becomes saturated and the solvent action ceases.

Limestone caverns have two more or less distinct periods in their history; in the first stage, that of solution, the channel is filled with water and is gradually enlarged, and in the second stage, that of deposition, the cavern is emptied of its water and stalactites are formed from the roof and stalagmites built up from the floor

FIG. 93. — Limestone platform, a Karst Landscape, Chapel le Dale, Yorkshire, England. (Photograph by Prof. S. H. Reynolds)

by the solution and redeposition of calcium carbonate. The withdrawal of the water may be effected in many ways: as, for instance, the lowering of the drainage level of the country through the down-cutting action of the surface streams; the opening of new channels through the rock; a diastrophic movement of upheaval, which would result in lowering the drainage level with reference to the cavern floor, etc., etc. It is not necessary that all the water be drawn off; deposition begins as soon as part of the cave is filled with air, and meteoric water can percolate through the limestone roof. Streams may continue to flow along the floor, or in pools

and ponds held in depressions, but the formation of stalactites and stalagmites does not take place under water.

Many caverns, in various parts of the world, are famous for the beauty or the bizarre character of their stalactites, and the caverns of Luray, in Virginia, and the Carlsbad Caverns, in New

Fig. 94. — Jenolam Cave, Australia. (Geol. Surv., Canada).

Mexico, are well-known instances of this. The mode of formation of these remarkable objects has been carefully studied, both in caverns and, under more favorable conditions, on the under side of masonry arches, as of bridges and viaducts which are exposed to the weather. As before remarked, all natural waters, even rain-water, contain CO_2 in solution and, in passing through the soil, an additional quantity is absorbed. First converting the calcium carbonate into a bicarbonate ($CaH_2(CO_3)_2$), the latter

FIG. 95.—Landslip, initial stage, Smartville, Calif. (Photograph by Gilbert, U. S. G. S.)

is dissolved by the carbonated water. When a trickle of water comes down through the cavern-roof and a drop hangs on the free side, exposed to the air, most of the carbon dioxide escapes and this causes the deposition of a ring of calcium carbonate around the drop. A continuance of this process lengthens the ring into a tube, which gradually fills up with the deposit and the tube becomes a solid rod, forcing the water to glide down the outside of the rod and thus very gradually increasing its diameter and its length.

When the drop falls from the roof of the cavern to the floor, it begins the formation of a stalagmite exactly beneath the stalactite and, as the latter grows downward, the former grows upward, until the two meet and join, forming a pillar, which will be en-

larged in diameter, so long as the percolating water continues to follow the same channels. Slight shifts in the flow of water produce the fluting and drapery effects and the deposit is a hard, dense, finely crystalline travertine which is translucent in thin pieces.

While the motion of the ground water is too slow to effect any mechanical abrasion, yet this water brings about important mechanical changes in an indirect manner. Masses of soil, or

Fig. 96.—Landslip of 1830, near Axmouth, Devonshire, England. The mass slipped to the left, opening the trench. (By permission of the British Association for the Advancement of Science)

talus, lying on steep slopes and saturated by heavy rains, may have their weight so increased as to glide downward in landslips, or rock-slides, as the case may be. The gliding is much facilitated if the moving mass rests upon a bed of clay which is lubricated by the water. These landslips have repeatedly had disastrous results and, naturally, are most frequent and extensive in the mountains, but they also occur in lowlands where conditions of slope and clay beds are favorable, as in the famous landslip of 1830 at Axmouth on the south coast of England, the effects of which are still visible.

In the Alps there has been a long succession of rock-slides, some

of which have resulted in great loss of life and destruction of property; space permits the mention of only a few of the more celebrated ones. In 1348 the south side of the Villach Alp slid down, burying 13 villages in the débris, and in 1662 the Schlaggendorf peak lost nearly 1,000 feet of its height from a rock-slide. The fall of the Rossberg in 1806 buried four villages and is one of the best known of these disasters, as is also the great rock-slide at Elm in 1881, which buried the valley and the opposite slope under twelve million cubic yards of rock. The Elm rock-slide

FIG. 97. — Rock-slide from Turtle Mountain, Frank, Alberta. Débris in foreground from slide. (Photograph by MacKay, Geol. Surv., Canada)

was, to some extent, artificial, for the opening of stone quarries removed the supports of the mass.

Sir William Conway describes "the formation of Gohna Lake in the Central Himalayas, where the spur of a large mountain mass pitched bodily into the valley below. The front of the mountain had been undermined by springs until there was no longer sufficient support, and in the twinkling of an eye a large part of the mountain slid down and shot across the valley, damming its river with a lofty and impervious wall. — It is estimated that this slide carried with it 800,000,000 tons of rock and débris."

Similar phenomena have been observed in North America, as

in the celebrated landslip of 1826 in New Hampshire, which was a major disaster, but incomparably greater was the great rock-slide at Frank, in the Canadian province of Alberta. In 1903, the entire face of Turtle Mountain fell and formed a huge avalanche of rock fragments, estimated at 40,000,000 cubic yards, which rushed across the valley and far up on the opposite slope, while Old Man River was dammed into a lake. Several agencies combined to produce this vast rock-slide, but the chief agents were an unusual amount of ground water and a severe frost which followed warm weather.

FIG. 98. — Profile of Turtle Mountain, showing scarp left by slide of 1903. (Geol. Surv., Canada)

The slides in the Panama Canal, notoriously the great Cucaracha Slide, added enormously to the amount of material excavated in the Culebra Cut. The Cucaracha Slide began to slip almost as soon as the French engineers began work upon it in 1889 and is still in motion, requiring the constant use of dredges. The movement is at a maximum in the heavy rains of the wet season, when the ancient volcanic mud-flows become exceedingly slippery.

B. Springs

Springs are openings through which the ground water reaches the surface and could not exist were the land entirely free from

irregularities, for gravity controls the movement of underground waters and the source of a spring, however distant it may be, must be above its mouth. A subterranean stream may be confined, as in a pipe, and subjected to a great hydrostatic pressure, which may seem to make the water flow upward, as when a spring pours out from a deep fissure, or rises on the top of a hill. But these are no more real exceptions than a fountain which throws its jet high into the air; in all cases the source is above the outlet, though it may be many miles away, and it is this elevation which causes the necessary pressure.

Rocks differ greatly in their permeability to water; some, like clay and marl, are quite impervious, while others, like sand, many sandstones, and conglomerates, are very porous and consequently permeable. Often, a rock which itself is impervious allows easy passage to water through innumerable joints, fissures, and crevices. The ground water, below the level of its table, spreads laterally, and its downward passage is checked or, it may be, prevented by some impermeable bed. When a valley intersects the ground water level, a line of springs is formed, especially if a relatively impervious bed, usually clay in some form, overlain by porous, water-bearing beds, crops out on the surface. These are the common and abundant *hillside springs* so familiar to all visitors to the country. If there is sufficient flow of water, the spring is the source of a little stream, and the tendency is for the spring to work back into the hill by undermining and thus to lengthen the stream which flows from it. This *recession of spring heads*, as it is called, may be a very important factor in the development of river systems.

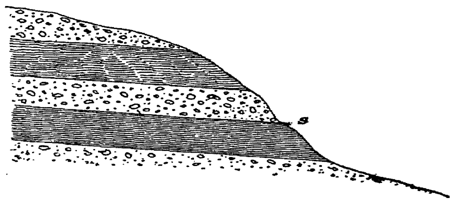

FIG. 99. — Arrangement of strata which causes hillside springs. The lower close-lined bed impervious; *S*, a spring.

When a series of water-bearing strata, underlain by an impermeable one, is inclined, the water moves along the surface of the impervious bed in both directions, upward and downward, so long as the line of saturation, or water table, is above the impervious bed at the latter's highest point. If such a series of strata run

through a ridge, cropping out on both sides, there will be a line of springs on each side, though the lower side, toward which the beds "dip," or are inclined, has more copious and durable springs. When, after a prolonged drought, the water table drops below the upper outlet, the springs on that side give out. The water supply of Heidelberg is derived from a remarkable spring, the Wolfsbrunnen, which always yields in abundance, though the dip of the strata would carry the water in the opposite direction, were not the line of saturation above the spring.

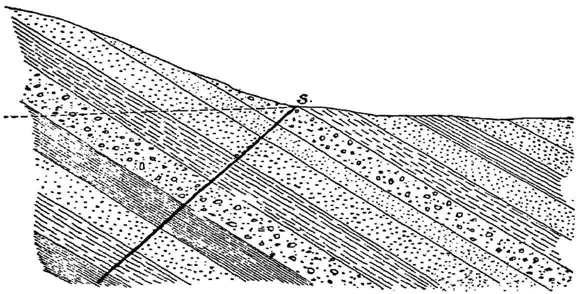

FIG. 100. — Diagram of fissure spring. The heavy line represents the fissure along which the water rises; *S*, a spring.

1. *Fissure Springs*, which are larger and more durable than those of the ordinary hillside type, are formed where a deep crack transects a series of inclined beds, some pervious, others impermeable. The water, descending along an impervious bed, reaches the fissure under pressure and goes down into that, until it is filled to capacity with water, when the water rises to the surface and forms a line of springs along the fissure. The porous beds receive their supply from the rain which falls upon their outcropping edges on the hill tops and sides and thus, as is necessarily the case, the source is above the outlet.

An artesian well (so named from the province of Artois in France) is an artificial fissure spring, in which a pipe is driven down through a series of inclined beds, of permeable and impermeable character, until water under pressure is tapped, when it rises in the pipe to

a height determined by the pressure. If the pressure is sufficient to force the water to the surface, it forms a flowing, or spouting, well; if not, the water must be raised by pumping. Ideal conditions for artesian wells are found in a basin of folding, when the strata dip toward the center of the basin from all sides, but such conditions are not essential. Whenever a pipe driven through inclined beds can tap a supply of water under sufficient pressure, flowing wells can be obtained. These conditions are given by the coastal plain of New Jersey, and very deep flowing wells have been driven at Atlantic City, Asbury Park, and elsewhere — in the James River Valley of North Dakota, in Texas and many other regions. Though artesian wells were not put down in Artois, the first in Europe till the twelfth century, the Chinese had bored them before the beginning of our era.

2. *Underground Streams* furnish a third type of spring, which is peculiar to limestone regions. The solubility of limestone makes the formation of caverns and subterranean channels very common where thick limestones occur, and in such regions the minor streams generally pursue more or less of their course underground. Such streams are often both subterranean and on the surface, when the season of rains or melting snows fills up the underground water courses and the surplus must flow in the surface channel. When the surface of the ground cuts across an underground stream, a great spring results. Silver Spring, in Florida, is navigable for small steamboats to the very head. Below Great Falls, Montana, the valley of the Missouri River intersects a subterranean water course, and the Giant Spring, a truly remarkable phenomenon, is the result. Another such spring rises in the bed of the river, and with such force that the bulge of the surface is conspicuous from the river bank.

3. *Mineral Springs*. Almost all spring water contains in solution various solid substances dissolved from the rocks through which the water has passed, and when these solids exceed 1 per cent by weight of the water, the spring is called a mineral spring. The term is often applied, more loosely, to springs which are highly charged with carbon dioxide and are effervescent when they reach the surface. Of dissolved solids the commonest are the carbonates and sulphates of calcium and magnesium, common salt, soda, borax, etc., etc. Water carrying ferrous carbonate ($FeCO_3$) in solution is called *chalybeate*.

Water that contains very small quantities of calcium carbonate is called *soft;* when it is present in considerable amount, the water is *hard.* This is a question of such practical importance that in France and Germany scales of hardness are employed, one degree of the scale being one part of the carbonate in 100,000 parts of water. The German scale is calculated for the oxide CaO, the French for the carbonate $CaCO_3$, so that 100 degrees of the French scale are equivalent to 56 of the German. When the water is of

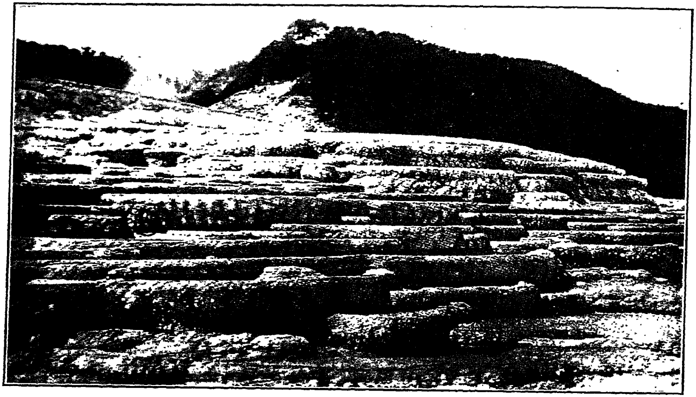

FIG. 101. — White Terrace, New Zealand, spring deposit of travertine. (Gift of J. Greenlees, Esq.)

more than 32 degrees hardness French (18 German), it is considered unfit for drinking. Hard water decomposes soap, converting it from a soluble soda-soap into an insoluble lime-soap and hence it is unsuitable for the laundry, and, even more important, when used in steam boilers, it deposits a dense stony *scale*, which has been the cause of many boiler explosions. By keeping the water from contact with the steel wall of the fire-box, the plates are heated red hot and so softened that they can no longer resist the steam pressure. So great is the importance of boiler scale that processes and apparatus for water softening are extensively used in limestone regions.

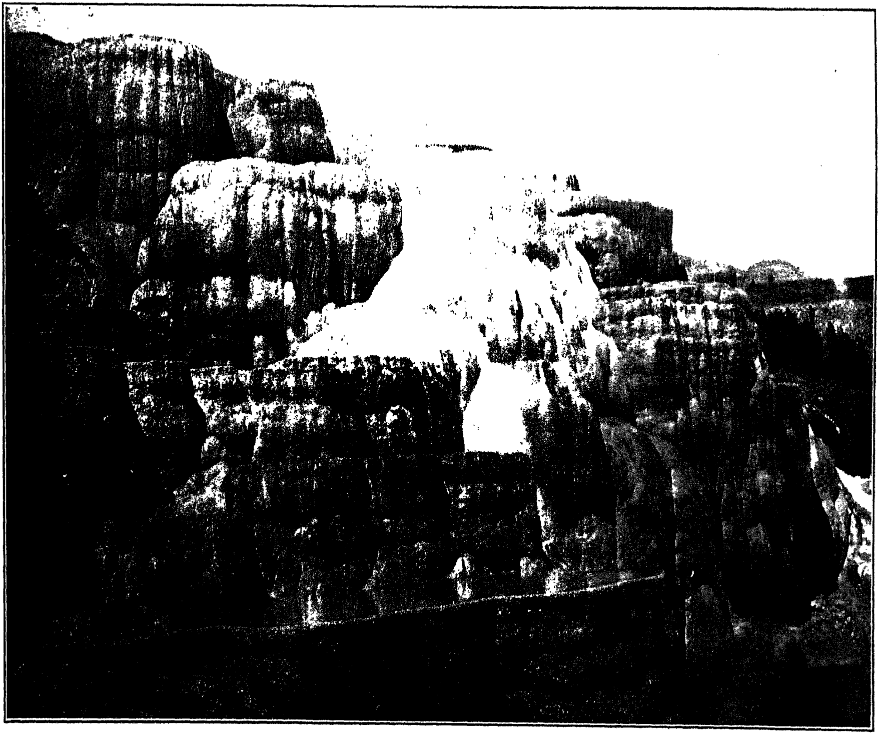

Fig. 102.— Travertine terrace, Mammoth Hot Springs, Yellowstone National Park. (U. S. G. S.)

4. *Spring Deposits* (see p. 184) may be accumulated to great thickness, but are never of very extensive horizontal extent. Much of the most common and important of these deposits are of calcium carbonate and they are made by chemical or organic agencies, or both in coöperation. As has been repeatedly remarked in the foregoing pages, calcium carbonate is soluble in water containing CO_2 by converting the limestone into calcium bicarbonate, $CaH_2(CO_3)_2$, and the amount of the gas which the water will dissolve is determined by the pressure, though solubility of the limestone is not increased by pressure or temperature. When the water comes to the surface and the CO_2 escapes, the calcium carbonate is deposited, often by the aid of plants, which withdraw the CO_2, reduce the bicarbonate to carbonate, and thus render it insoluble.

Hot-spring deposits throw some light upon the genesis of metalliferous veins, which have been a subject of much controversy. Steamboat Springs, in Nevada, are now forming a siliceous sinter, either pure, or mixed with calcium carbonate, and this contains determinable amounts of the sulphides of mercury, lead, copper, arsenic, and antimony; gold and silver are present and traces of several other metals. In a shaft put down in a neighboring gravel, Lindgren discovered stibnite (antimony sulphide) crystals, together with grains of pyrite, or marcasite (FeS_2).

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CHAPTER XIII

RIVERS

Rivers, including all running streams, surface and underground, in that term, are very efficient agents in all three kinds of geological work, erosion, transportation, and deposition, but they differ from the atmosphere and the sea in being much more subject to variation in their activities as the geographical cycle advances. In youth, maturity, and old age, and in rejuvenation, river systems pass through stages of development which are much more distinctly marked than in the case of the other surface agents, and this development is conditioned and controlled by the rocky structure of the country in a manner that is peculiar to rivers. It is the history of rivers that explains the paradoxical and otherwise unintelligible behavior of so many streams, when it would appear as if they must have begun their careers by running uphill, when they seem to avoid the easy path and take the difficult one. All over the world, rivers are seen to cut through mountain ranges in a way that would seem to be impossible, if rivers cut their own channels.

Erosion by Rivers. The destructive work of rivers is, in the aggregate, far less important and extensive than that accomplished by the atmosphere, but it is much more striking because it is concentrated along narrow lines, not spread over the entire land surface. Some of the most magnificent examples of scenery, such as the Grand Cañon of the Colorado, are principally the work of the river, though even here, atmospheric coöperation has been an important factor in producing the wonderful result.

A certain amount of solution and chemical decomposition is accomplished by a river upon the rocks of its bed and, in limestones, this may be considerable, especially if the water is charged with organic acids from a swamp or peat-bog. Limestone regions are marked by a paucity of surface rivers, the smaller ones of which pass into the subterranean channels which they have made by dissolving the rock. These subterranean streams may, or may not, reappear upon the surface.

Very much more effective than the chemical is the mechanical erosive work, which is dependent upon the velocity of the current and varies directly as the square of that velocity. The velocity of a current is the rather complex resultant of several factors, the chief one of which is gravity; the steeper the slope of the bed, the swifter is the flow of the water, with the maximum in the vertical drop of a cataract. A second factor, important in large streams, is the volume of water; with equal slopes the velocity varies as the cube root of the volume. That is to say, that if two parallel streams flow down the same slope, one of which has eight times as much water as the other, it will flow twice as fast. This is exemplified by the bayous of the lower Mississippi, which have the same slope of bed as the river, for they leave it and return to it; yet, while the river has a swift current of five or six miles an hour, in the bayous the water seems hardly to move at all.

Clear water can do little to abrade rock except in the way of solution and, in the case of a stream flowing in a bed of limestone, the solvent action becomes important. When the Niagara, above the falls, was diverted, and part of its limestone bed exposed to view, this bed was rough and jagged, corroded and irregular, to an entirely unexpected degree, due to the solvent action of the water. (See Fig. 111.) Clear water can also remove loose materials, sand, soil, and the like. When, in 1900, the Colorado River broke into the Salton Sink in southeastern California, which is below sea-level, it cut a deep trench through the alluvial soil with incredible rapidity, and it was with the utmost difficulty that the river was forced to return to its own channel. The great problem in the control of the Mississippi is that presented by the soft materials through which the lower river flows.

A stream which flows in a channel of hard rock cuts into its bed by means of the sand and gravel which it sets in motion, the stream supplies the power, just as does the wind in desert erosion, but more effectively, because many rocks are somewhat softened by being wet. The cutting materials are themselves abraded and worn down by collision with one another and with the bed-rock; angular blocks are speedily worn into cobble stones and these into pebbles, the shape of which is determined by the material and the velocity of the current. Quartz pebbles are rounded and made irregularly spheroidal by being rolled along the bottom, while some others, especially those made of slate, or sandstone, are discoidal.

In the case of complex minerals, the abrasion is accompanied with some chemical decomposition, as has been demonstrated by rotating orthoclase crystals in a drum half filled with water. When, after the equivalent of a journey of twenty miles, the feldspar was ground down to mud, the water showed the presence of potash in solution, though powdered orthoclase standing under water for the same time did not give the reaction for potash. (Daubrée.)

FIG. 103. — Porth-Cadjack Cove, near Portreath, Cornwall, England. Valley made by a fault which is seen in cliff. (Geol. Surv. Gt. Brit.)

The manner in which a stream cuts its channel and deepens it into a gorge varies much according to circumstances, though the differences are in the details of the process, the principle being the same throughout. Velocity of the current, character, arrangement, and large-scale structure of the bed-rocks, and climatic conditions, are the chief variable factors. A river which is subject to sudden fluctuations of volume, being now a rushing torrent and again nearly dry, is a much more efficient agent of destruction than one which maintains a more uniform quantity of water, or fluctuates slowly. Streams cut their own channels, yet they take advantage of special lines of depression or weakness. A fault or fracture and dislocation of the rocks is frequently selected by a stream, and, occasionally, a trench-fault, or *Graben*, offers a ready-made channel. In Fig. 103 is seen a particularly favorable case of a stream, the course of

which is determined by a fault, at Porth-Cadjack Cove, Cornwall, in England. The cliff in the foreground cuts across the course of the fault and shows it in section. The Au Sable Chasm, a remarkable stream-cut gorge, is in part determined by a line of fault, partly by joints, which have very great influence in locating minor streams.

Of the various ways in which a stream effects the cutting of its channel, the commonest, perhaps, is by horizontal abrasion of the

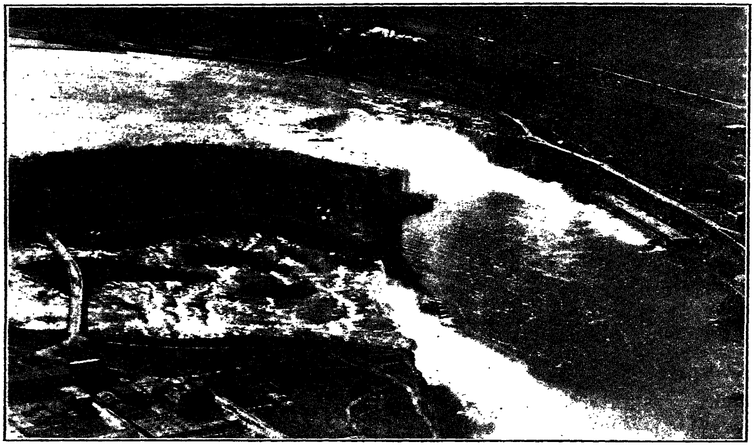

FIG. 104. — Niagara Falls from an altitude of 10,000 feet. (Courtesy of the Chief of Air Corps, U. S. Army)

bed. Few data are available for the rate at which this work is carried on and, of course, the rate varies much in different streams, but the boring of the Sill tunnel in the Tyrol gave an opportunity to determine this rate under exceptionally favorable conditions. The rock from the tunnel was dumped into a water-way paved with granite slabs a yard in thickness, and swept down by a very swift current of water; so rapid was the abrasion that the granite was worn through in a single year. This is a very high rate; no doubt entirely exceptional, but it serves to show what a stream

can accomplish if there is a rapid current, abundant supplies of water and of abrading material.

A second method of gorge cutting is by the retreat of a waterfall, which works backward like a vertical saw and lengthens its gorge as it retreats. The manner of retreat depends upon the arrangement of hard and soft rocks in the bed, and this determines whether the fall is to become a rapid by the faster wear of the surface rock in the bed, or whether it retreats by undermining. The former case is exemplified by the Falls of the Rhine at Schaffhausen, which are in a limestone of uniform hardness, and Niagara

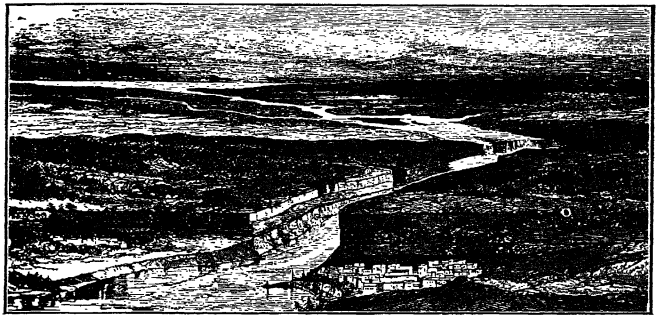

Fig. 105. — Diagram of the Niagara River and Falls from Lake Erie to Lake Ontario. (After Lyell; courtesy of Messrs. John Murray, London)

is a well-known example of the latter. Above the falls the bed is in a hard limestone which yields but slowly to the abrading action of the water, which is singularly free from sediment, owing to the "settling basin" of Lake Erie. Beneath the limestone is a soft shale, which yields rapidly to the action of spray and especially to the winter's frost. Consequently, the limestone is undermined and projects as an overhanging ledge, which, when no longer able to support its weight, falls in great masses. In this manner the verticality of the cataract is maintained and the retreat spasmodic, averaging about three feet a year. The last great collapse of the crest was in January, 1931, and affected the American Fall.

The little river Simeto, in Sicily, is of particular interest, because the history of its gorge is so well known and because it was studied

and described by Sir Charles Lyell. In 1603 a lava flow from Ætna dammed the course of the stream and formed a lake which rose to the level of the lowest part of the lava, followed that to the downstream side of the lava flow and there formed a cataract, which immediately began to cut a ravine. The lava was not slaggy or porous, but solidified and cooled into an extremely hard rock. When Lyell visited the site in 1828, he found that in two and a quarter centuries the stream had cut a gorge 40 to 50 feet deep and varying in width from 50 to several hundred feet. "On entering the narrow ravine where the water foams down the two cataracts, we are entirely shut out from all view of the surrounding country; and a geologist . . . can scarcely dissuade himself from the belief that he is contemplating a scene in some rocky gorge of very ancient date. The external forms of the hard blue lava are as massive as any of the oldest trap-rocks of Scotland. . . . But the moment we re-ascend the cliff, the spell is broken, for we scarcely recede a few paces before the ravine and river disappear and we stand on the black and rugged surface of a vast current of lava, which seems unbroken and which we can trace nearly to the distant summit."

Another method of excavation is by means of linking together a line of pot-holes, by means of which a small inner gorge is formed. A cataract in its retreat forms a series of these holes, each one cutting away the partition between itself and its predecessor, as is exemplified in Watkins Glen, New York. How frequent and important this process is cannot well be stated, as observations are lacking.

A gorge cut out by a stream has, at first, vertical walls, but these walls are attacked by the atmosphere, the stream removing the débris as fast as it is formed. As the upper part of the gorge was usually the first formed, it has been exposed to the atmospheric attack for the longest time and is thus the widest. The vertical sides of the gorge become sloping and the gorge is then V-shaped in cross-section. This widening continues until the river valley is broad, with gently sloping sides, though the gorge form may be retained where the stream crosses especially hard bands of rock, as in the "gaps" of the Delaware, Susquehanna, Potomac, and other Atlantic rivers, where they cut through the mountains. A steep-sided gorge is thus relatively youthful, but in an arid climate it will persist for a much longer period than in a pluvial one. (See

Frontispiece.) In the Far West, where the cañon form of gorge is so frequent, the dry climate preserves it much longer than on the pluvial Atlantic slope. In the region of heavy rainfall and sharp winter frost, only the very youthful streams have retained the narrow, steep-sided gorge.

These youthful streams are all in the glaciated area of the continent, from which the ice disappeared only a few thousand years ago, leaving behind it a mantle of glacial drift which obliterated the minor streams and valleys and over much of the Middle West actually reversing the direction of drainage. The thousands of driven wells and borings which have been put down for water, oil, and gas give the data for mapping this ancient drainage system. The greater rivers, such as the Connecticut, the Hudson, the Delaware, etc., retained their valleys and re-occupied them, when the ice disappeared, but innumerable new streams were established on the drift surface, which had a general southward slope, and speedily cut through this loose material into the underlying rock. The depth to which gorges can be cut in the rock depends upon the height of the region above sea-level, for streams which enter the sea cannot cut below that level. The many picturesque gorges in New England and New York, such as the Au Sable Chasm and Watkins Glen, are all post-Glacial in date of origin and there has not been time for the atmosphere to widen them into the typical V-shaped stream valley.

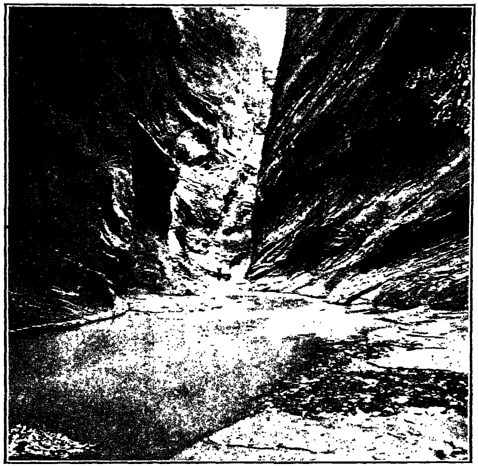

Fig. 106. — Cañon of Virgin River, Utah. (Photograph by Hillers, U. S. G. S.)

Though not the deepest of existing river-gorges, the cañons of the Colorado River are among the most remarkable examples of river erosion. The Green River and its tributary, the Yampa,

FIG. 107. — Au Sable Chasm, eastern Adirondack Mountains, N. Y. (Photograph by J. A. Glenn, Albany, N. Y.)

make magnificent cañons, where they cut through the Uinta Mountains. After the junction of the Green and Grand rivers, the Colorado, formed by this junction, enters the region of the High

Plateaus of Utah and Arizona, which reach an elevation of over 10,000 feet. The Grand Cañon is over 200 miles long and from 4,000 to 6,500 feet deep. The diastrophic upheaval of the region, whether gradual or spasmodic, has kept the river at the height of its efficiency, like the feeding of a log to the saw in a saw-mill, and enabled it to cut to such profound depth. Whether the rise

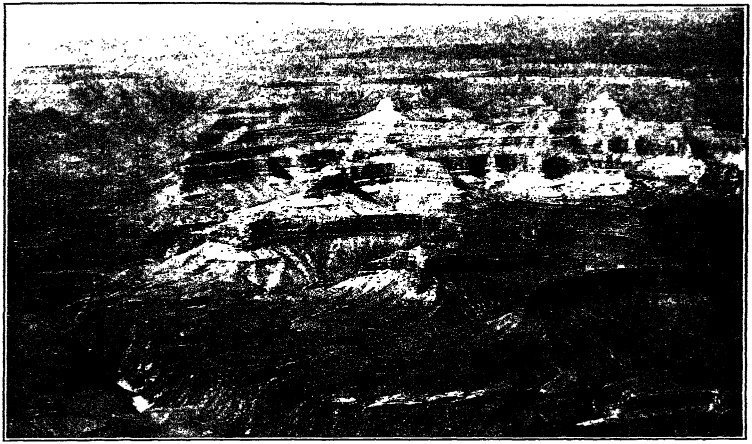

FIG. 108. — Grand Cañon of the Colorado River, Ariz. (Courtesy of the Chief of Air Force, U. S. Army)

is still in progress is not known, but the river-bed is still 1,000 feet or more above the sea, the current is extremely swift, and erosion is still rapid.

In cross-section, the cañon is in two parts, the outer and upper, and the inner, lower gorge. As the river has cut from above downward, the outer gorge is older and much wider than the inner. The width varies, but is as much as thirteen miles from rim to rim, and the walls of this older portion, which are sedimentary rocks, have been carved by the atmospheric agencies into the wildest and most extraordinary labyrinth, which, together with the brilliant coloring and the grand scale of the topography, make the

cañon the marvelous spectacle that it is. The floor of the outer gorge is nearly flat and several miles wide, while the inner cañon, some 2,500 feet deep, is very narrow and is cut through much harder, mostly crystalline rocks. The relative youthfulness of the inner cañon and the greater hardness of its walls account, to some extent, for the extraordinary difference in the width and the

FIG. 109. — Victoria Falls of the Zambesi River, South Rhodesia, looking up the river. (Courtesy of the Aircraft Operating Co., London)

sculpturing of the two parts of the Grand Cañon, but, very probably, there is another reason for this difference, namely, the change of climate from moist to arid, which followed the disappearance of the ice of the Glacial Epoch. That such a change actually took place, there is abundant evidence and in the region of the Rocky Mountains and the High Plateaus there are many dry cañons, which have been abandoned by the streams that cut them; the rainfall no longer suffices to maintain these streams.

The gorge of the Zambesi in South Africa, which has been excavated to a depth of 400 feet in a mass of hard, basaltic lava, has been carved by the retreat of a cataract, but in an altogether exceptional manner. Above the Victoria Falls (one of the most wonderful and beautiful spectacles in the world) the river is more than a mile wide and plunges into the Chasm, which, strange to

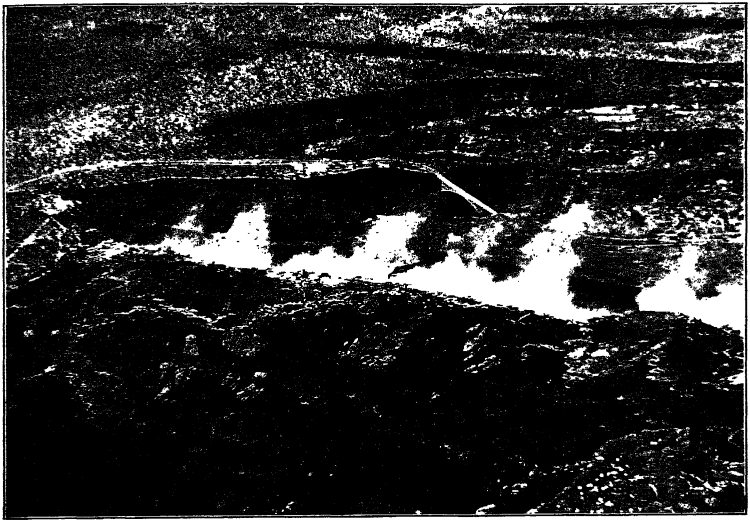

FIG. 110. — Victoria Falls, looking downstream, showing the zigzag gorge below the Falls. Dark area in the foreground is the river above the Falls. (Courtesy of the Aircraft Operating Co., London)

say, runs directly across the course of the stream and owes its position to a line of fault. From the Chasm the only outlet is by means of a narrow gateway of only 50 to 60 yards in width, through which the water rushes with tremendous velocity. The gorge continues for 40 miles in a series of zigzags, sharp bends, almost at right angles, the location of which has been controlled by the lines of jointing in the rock and of which there are a hundred

or more. A new zigzag would seem to be forming at the western end of the Victoria Falls, where the separate cataract, known as Leaping Water, has already cut 25 feet below the level of the main fall and must eventually divert the whole stream.

Lake Ilopango, in the Central American republic of Salvador, which is volcanic and so surrounded by steep mountains as to have no room for horizontal expansion, rose four feet in the first days

FIG. 111. — Bed of Niagara River at rapids above the Falls, exposed by diversion of the water. (N. Y. State Survey)

of January, 1880, probably because of volcanic disturbances which gave rise to new islands in the middle of the lake. The outlet stream, called the Jibon, which was, before the disturbances began, very shallow and only twenty feet wide, was converted into a furious torrent. This great increase in volume and velocity correspondingly increased the erosive power of the current, which cut down its channel through the volcanic rocks to a depth of thirty-five feet. This, in turn, permanently lowered the lake-level more than thirty-four feet.

As a river cuts downward into its bed, it diminishes the slope of that bed and therewith the velocity of the stream, so that the vertical excavation is done at a constantly diminishing rate and, unless the region is elevated, must come to an end. When the limit is reached and vertical excavation ceases, the river is said to be at *base-level*, or to be base-leveled, and then the course of the stream, from source to mouth, approximates a parabolic curve, such as is almost perfectly exemplified by the Loire, in France. The general and permanent base-level is that of the sea, but there may be local base-levels, where rivers end in lakes that are below the sea, such as the Dead Sea, which is 1,300 feet below the Mediterranean, and the Caspian, 86 feet below. Streams which enter a lake have their base-level that of the lake, but inasmuch as, geologically speaking, lakes are ephemeral and rivers much longer-lived, the streams will gain a new base-level when the lake has disappeared. The tributaries of a stream have their base-levels determined by the trunk into which they flow and, as that trunk stream lowers its channel, the tributaries keep pace with it.

FIG. 112. — Pot-hole, filled with water, Glens Falls, N. Y. (N. Y. State Survey)

The velocity of a stream is subject to local variations, falls, rapids and eddies alternating with reaches of quiet water. At the foot of cataracts, or at the bottom of eddies, the water acquires a circular motion, causing loose stones and pebbles to gyrate on the bottom, and if that bottom is of hard rock, the revolving stones will cut a circular shaft. The diameter and depth of the *pot-hole*

(kettle hole, or giant kettle) so generated will increase so long as the waterfall or eddy remains at the same point and as the cataract usually recedes by sudden increments, owing to the undermining and fall of the crest, the pot-holes remain circular and a new one is started at the new position of the cataract. Pot-holes are also generated in the bed of a glacier, where a stream, flowing on the surface of the ice, pours down through an opening in the ice and sets stones revolving on the rocky floor. The glaciated part of the United States, especially near the margin, where the ice was relatively thin, has innumerable pot-holes which are filled up with drift and are therefore discovered only by accident. Some of these are large chambers of surprising dimensions and regularity; pot-holes of fifteen feet or more in depth and diameter have been found and they testify to the length of time during which the waterfall through the ice remained stationary.

Most of the Atlantic rivers of North America have already reached base-level, and such rivers as the Connecticut, Delaware, Susquehanna, Ohio, etc., etc. are not deepening their channels.

The erosive work of a river does not cease when base-level is reached, for the stream cuts laterally, broadening the channel, and excavating a valley much wider than itself, because it swings from side to side, undercutting and undermining the banks; and this continues as long as the current has any perceptible velocity, especially, of course, when flowing in soft, alluvial soil.

Transportation by Rivers is the most important of their geological activities, for they carry away the débris furnished by their own activity and that of the atmosphere. No other of the surface agents is so efficient in transporting to the sea the waste of the land as is the river. This transportation is of two kinds of material, that which is in solution and that which is in larger and smaller pieces, grains, and particles. The solid material is, in part, pushed along the bottom by the current, which is unable to lift it and, in part, carried in suspension.

Materials Mechanically Carried. The transporting capacity of running water varies as the sixth power of its velocity, which means that if the speed of the river be doubled, it can carry along sixty-four times as much sediment as before. This very surprising result has been demonstrated both experimentally and mathematically. The formula refers more particularly to the coarser and heavier materials which are pushed along the bottom and does not

apply to the very fine particles of clay, which are in a colloidal state and remain suspended indefinitely, even in still water. From this it follows that a slight acceleration of the velocity of the current will cause a stream to increase its load and a slight retardation will make it drop much of the material carried. Such a river as the lower Mississippi, flowing through alluvial deposits, and with continual variations of volume and velocity, seems to act with the utmost capriciousness, cutting away the bank on one side, building it up on the other, forming a bank or an island around a snag and sweeping it all away the next week. Small increases or decreases in the swiftness of the current produce remarkable changes in the bed and banks.

The buoyancy of water is an important factor of its transporting power, because, when any substance is immersed in water, it loses weight to an amount equal to the weight of the water displaced. The specific gravity of most rocks is from two and one-half to three and, when immersed, they lose from one-third to two-fifths of their weight in air. The shape of the fragments also has an influence in determining the speed of current necessary to move them; the larger the surface of a particle in proportion to its mass, the more easily is it carried in suspension. Flat grains, or scales, are carried farther than round ones, while the rounded pebbles are more easily rolled along the bottom when too heavy for the current to lift.

The extraordinary ratio between velocity and transporting power explains the destructiveness of sudden and violent floods, of which there have been so many in the past century. The terrible flood which, in 1889, overwhelmed Johnstown, Pennsylvania, with frightful loss of life and destruction of property, remains a particularly instructive example, because it was so carefully observed and studied during and after the catastrophe. The flood was caused by the bursting of a dam near the head of the Conemaugh River, down the narrow valley of which the immense volume of water rushed at a speed of twenty miles an hour. An eye-witness declared that on the front of the wave no water was visible, but a confused mass of soil, rocks, trees, and frame houses, which were held by the stone railroad bridge near the town. The soil was swept away to bed-rock; great locomotives and steel girder-bridges were carried for miles like so many chips; heavy steel rails were twisted into corkscrew spirals or broken into lengths of

two or three feet. All buildings within reach of the water were destroyed, and, after the flood had passed, the scene of destruction was indescribably dreadful.

The greater part of the débris carried by a river is supplied by the work of atmospheric destruction; rain washes in fine material and frost and landslips bring in the larger masses which are transported by mountain torrents. To this the river adds the material derived from the erosion of its bed and its banks, which fall in from undermining. These statements, except the last one, do not apply to rivers like the Missouri and lower Mississippi, which flow in beds of soft alluvial soil, which they pick up and carry away in great quantities; their burden is chiefly of their own making.

Fig. 113. — Kittatinny Ridge from 10 miles south showing the level skyline and the widening of the Delaware Water Gap at the top. An intervening ridge conceals lower part of Gap.

Materials in Solution. A variable amount of dissolved substances is always present in river water and these are the same as those found in spring water, from which they are mostly derived by the river, though in somewhat more diluted form. Rain water falls directly into the stream and, in much larger quantity, runs in from the banks, more than balancing the loss by evaporation. In very dry regions, where this influx of rain water is at a minimum and where streams are fed almost entirely by melting snows on the mountains, the loss by evaporation is very much greater and the river water becomes a more concentrated solution of salt, soda, borax, alum, calcium carbonate and sulphate or the various saline compounds which are included in the comprehensive term *alkali*. Such streams end in a salt lake or die away in the desert sands and their waters are unfit for use in varying degree.

A vast quantity of material, solid and in solution, is annually transported to the sea by rivers. De Lapparent calculates that the

amount so transported is 16 cubic kilometers; though accurate determination has been made for only a few rivers, this suffices to make an approximate estimate of the whole. Of material mechanically transported, the Mississippi discharges annually into the Gulf of Mexico an average amount of 7,471,411,200 cubic feet, enough to cover one square mile to a depth of 268 feet. To this should be added 2,850,000,000 cubic feet, the estimated amount of material in solution.

Rivers differ greatly in the amount of material transported per unit of volume, according to the slope of the land, velocity of the current, amount of rainfall, and the like. The great rivers of India, the Ganges and Brahmapootra, which enter the Bay of Bengal by common trunks, transport more than five times as much solid matter as does the Mississippi — in round numbers, 40,000,000,000 cubic feet. The great rivers of China discharge so much sediment that the whole Yellow Sea is discolored by it. The greatest of all rivers, the Amazon, owes its vast volume of water to the heavy rainfall, especially on the eastern side of the Andes, over its drainage basin. Though this basin is only twice as large as that of the Mississippi, the amount of water discharged is more than five times as great. The quantity of sediment carried has not been determined, but is probably in proportion to the volume of water, for the Amazon has built a submarine delta which extends out to sea for 125 miles and has depths of less than 10 fathoms over it.

Deposition by Rivers. Fluviatile deposits are becoming increasingly important in the history of the earth, and much that was formerly ascribed to lakes is now believed to have been accumulated by rivers. Much of the material laid down by streams has but a temporary resting place, and when the next high-water stage comes, is again picked up and carried away, but there are certain points in a river's course where deposition is more or less constant and where relatively permanent fluviatile rocks are formed. Tracing a river from its source in the highlands down to the plains and the sea, the slope diminishes and, with it, the transporting power of the stream. In the upper stream, which is a torrent in swiftness, only large stones can lie in the channel and even these are swept down when the stream is in flood. Farther downstream, with diminishing velocity, coarse gravel and cobble stones are deposited, but in swift streams the clashing and grinding of stones

along the bottom can be plainly heard in the Rhine so far downstream as the Lorelei. Still farther, fine gravel is laid down, then coarse sand, and next fine sand. In the lower reaches of a river like the Mississippi with bed of very gentle slope and but little above sea-level, only the finest silt is carried. There is a great

FIG. 114. — Boulders washed down by flood, Felch Gulch, Col. (Photograph by Cross, U. S. G. S.)

difference between the high and low stages of water as to the scouring and depositing at a given point, coarse materials being carried farther down at high water.

At points where the current of the stream meets a constant check, there will be constant deposition and thus bars and islands are built up in the channel, which will be permanent, unless there is some change in conditions. In the sand-bars and gravel-spits the upstream side is a gradual slope, ending abruptly on the downstream side, the spit advancing by having sand or gravel pushed up the gentle incline and dropped over the steep face, where it

forms inclined layers. Flattened and elongated pebbles arrange themselves in a slanting position, with tops downstream, so as to offer the least resistance to the current. When the stream is subsiding, the deposited material tends to assume a horizontal attitude, and thus a confused arrangement, known as *cross bedding* or *current bedding*, is the result. These apparently trivial features are of importance as enabling the observer to identify the deposits made in a river channel, which in cross-section form a lenticular body. It should be added that cross bedding is by no means confined to river deposits.

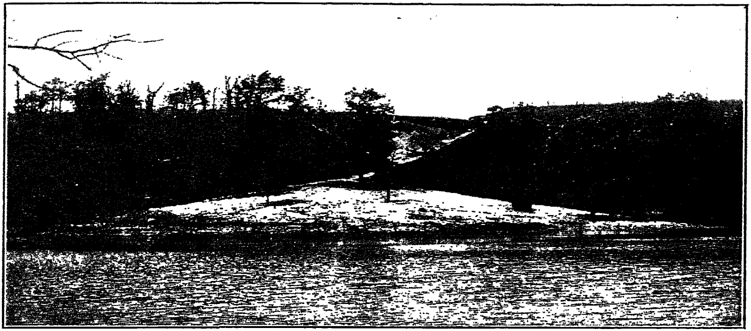

FIG. 115. — Youthful gulch and alluvial fan, Rock Co., Wis. (Photograph by Alden, U. S. G. S.)

Alluvial Cones or Fans. Where a swift, heavily loaded torrent debouches on a flat surface, its velocity is greatly reduced and most of the material carried is immediately thrown down and spread in a fan-shape from the mouth of the ravine down which the torrent flows. The thickness of the cone is greatest at the mouth of the ravine, the fan thinning and widening from that point. When several such torrents descend to the plain near together, their fans may coalesce and form a continuous fringe along the base of the mountain. The slope of the cone's surface diminishes with the size of the stream; in small streams it may be as much as 10°. These cones, or fans, are formed on the same principle as deltas and might properly be called terrestrial deltas; they occur on a

great scale in the Rocky Mountain and Great Basin regions. In the Argentine Republic, along the front of the Andes, temporary rivers, formed by the melting snow in spring, carry down enormous quantities of mud and fine sand and spread it out over the plain. Where rivers empty into the sea, this process of upbuilding is limited, but in interior arid basins, without outlet, very great thicknesses of river deposits may accumulate and, in conjunction with wind-made accumulations, many thousands of feet of sediment may form in such basins.

Fig. 116. — Alluvial fan, Emerald Lake, British Columbia. (Geol. Surv., Canada)

Flood Plains. Rivers are subject to floods, in which the vastly increased volume of water cannot be contained in the channel, but spreads out over the low ground on each side to an extent which is determined by the width of the valley, and the ground thus annually inundated is called the flood plain. Over this plain the water moves with greatly diminished velocity, causing the deposition of great quantities of sediment, the character of which varies in different streams. Usually it is very fine mud, like that of the Nile, but swift mountain streams spread coarse gravel over their flood plains, as does the Shoshone River in the Big Horn Basin of Wyoming.

The contact between the swift current of the channel and the almost stagnant water of the plain is very clearly demarcated and forms, on each side, a line of especially rapid deposition, which is built up above the flood level and looks like artificial levees (Fig. 118) because that line of contact retards the heavily loaded stream of the channel and therefore causes deposition. The unchecked

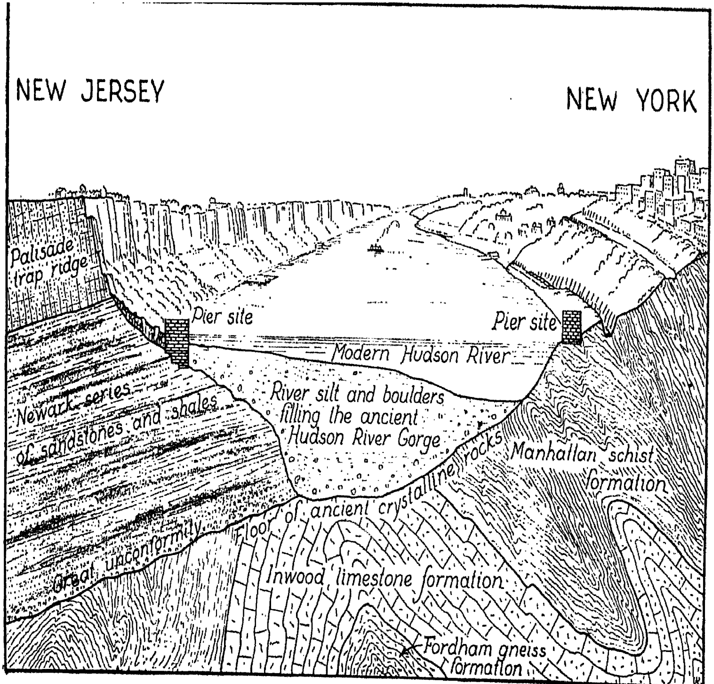

FIG. 117. — Generalized section across the Hudson River at the new George Washington bridge; vertical scale much exaggerated. (Courtesy of Prof. C. P. Berkey)

velocity in the channel itself usually causes scouring and deepening there, though the next season of low water may fill it up to the former level. Under other conditions, especially if the region be slowly subsiding, both channel and flood plain may be built up. The same result follows if embankments prevent the river from spreading over the flood plain, and, in such case, the embankments must be raised as the channel is filled. The principal river of northern Italy, the Po, has thus been restrained for centuries past

Fig. 118. — Kootenay River in flood, showing lines of deposition at contact of channel and flood-plain. (Geol. Surv., Canada)

and in part of its course flows in what seems to be an aqueduct. Past Ferrara it flows at a level above the house tops and is a continual source of danger.

An unrestrained river in flood converts the whole broad valley into a temporary lake, as in Egypt at high Nile. There the inundation is welcomed for the layer of mud which it leaves behind and to which is due the inexhaustible fertility of the country through five thousand years or more. That the same policy cannot be adopted for the Mississippi occasions enormous loss of valuable soil, which is carried to the Gulf. Even in the arid basins these temporary lakes may be formed; the fine silt deposited over the flood plain may all be carried away by the wind in the next dry season, leaving only stony wastes, or the flood-plain deposits may be added to the other deposits in filling the basin.

Even in climates of heavy rainfall, great interior basins occur, which, though they are drained to the sea, are deeply filled with river deposits. The interior of South America, drained by such rivers as the Orinoco, Amazon, Paraguay, etc., yields an example of such basins. Where there is abundant rain, the flood plain is thickly covered with vegetation which both protects and holds the river deposits. In arid climates, the flood plains are bare of vegetation for most of the year and the river muds are exposed to the sun. Areas of mud, thus exposed, shrink in drying and crack in deep fissures which inclose polygonal figures, as may be seen in any drying mud puddle. Cracks so formed are called *mud* or *sun cracks*, and may be preserved indefinitely in the rocks formed from flood-plain deposits.

Fig. 119. — Mud cracks, delta of the Colorado River, Mexico. (Photograph by Gilbert, U. S. G. S.)

In such accumulations there is apt to be a difference in the material thrown down in the earlier and later stages of the flood, because of the difference in the rate at which the water moves. After the river has ceased to rise, the water over the flood plain becomes almost stagnant and throws down very fine material.

After the flood waters have withdrawn, it is this fine mud which is dried and cracked in the sun, the cracks remaining open till the next high water. When the flood again arrives, it brings somewhat coarser material, often fine sand, which fills up the cracks and thus preserves their outline. Footprints of animals have often been preserved in similar manner, being baked hard in the hot sun and then buried under the deposits of the next flood. Mud cracks and footprints and even the impressions of rain-drops are frequently found in the rocks and give valuable aid in determining the conditions under which those rocks were formed.

In geologically ancient flood-plain deposits, which the rivers that made them deserted long ago, the old channels are indicated by coarser materials, cross-bedded sands and gravels cemented

into sandstone and conglomerate. When those channels are laid down on a map, their sinuous course, of great length in proportion to width, and their ramifying branches clearly mark them as an ancient system of drainage. The channels were often shifted and abandoned and then were covered over and buried by renewed deposition on the flood plain. Such channels and the broad, regularly stratified flood-plain deposits cover very extensive areas in South Dakota, Nebraska, and others of the Western States. Many, perhaps most, of the bad lands have been carved out of these soft fluviatile rocks, while some are lake deposits.

River Terraces and Old Gravels. The lower courses of many rivers, including most of those in the northern United States and some in the southern, are bordered by a succession of terraces that rise symmetrically on the two sides of the stream. Sometimes, as in several English rivers, the terraces are at different levels on the opposite sides. The formation of these terraces is due to the twofold activity of the stream in excavating one part of its valley and building up another. Owing to this combined excavation and building up of the flood plain, the trough of the river becomes so deep that floods no longer suffice to fill it, especially if the velocity of the current be maintained, or even increased, by a diastrophic elevation of the drainage basin. Then the river widens its channel and forms a new flood plain, cutting back the edges of the old one, which it no longer overflows, thus converting it into a terrace, which is a remnant of the old flood plain. This process may be repeated several times, forming a succession of terraces, one above another.

From this account it follows that the highest terrace is the oldest and the lowest is the last one formed. This seems to be an exception to the rule that in an undisturbed series of sedimentary deposits, the oldest must necessarily be at the bottom and the newest at the top; but the exception is only in appearance, not in reality, for the deposits of the terraces are not actually superposed, one on the other, but merely formed at successively lower levels. If the river flowed at a constant level, no terraces could be formed, but as it flows at lower and lower levels, the lower flood plain is the newer.

Asymmetrical terraces, which are either confined to one side of the river or are at different levels on the two sides, are formed when a river is widening its valley by encroaching on one side,

shifting the channel toward that side and deepening it at the same time. This will result in the formation of a series of terraces, each representing a former position of the river, on the side away from which the channel is shifting; if the shift be alternately in opposite directions, terraces will be formed on both sides of the river, but at different levels.

Another, less frequent, mode of terrace formation should be mentioned. If a river which has excavated a wide and deep valley has its velocity diminished by the subsidence of the region, the excavation will not only cease, but filling will take its place. The Hudson River, after cutting a deep rocky gorge, was so depressed as to be "drowned," that is, its valley was invaded by the sea and, for the most part, converted into an estuary. As a consequence, the gorge was filled with several hundred feet of mud. Should a reëlevation of the country take place, the rejuvenated river will immediately begin to cut a terraced channel through its own deposits. In such case, the deposits are a continuous body and those at the top were the latest-formed. The rivers Mersey and Irwell, in England, are believed to be examples of this mode of terracing.

Rock terraces in a river valley are the result of erosion only and are due to the harder ledges of rock exposed in the excavation. In all cases, terraces mark the successive levels at which the river has flowed and they do not imply, as would seem to be the obvious explanation, at first sight, that the river was once very much larger than at present, filling the space between the highest terraces, and that the lower terraces represent successive stages of shrinkage.

Bars. A bar is a shoaling of the water at the mouth of a river, because of the loss of velocity of the current, when meeting the still water of a lake or the sea. Though the sea may be violently agitated by waves, it puts an end to the flow of a river; currents in the sea may continue to transport more or less of the stream's load, but that does not prevent the formation of a bar at the river's mouth. The real mouth of the Hudson is six miles below Albany, where the river enters the tidal estuary, and there is a bar at that point. There is another bar at Sandy Hook, where the current of the ebb-tide, laden with sediment, enters the ocean and has its velocity checked, depositing its load, the tide acting like a river. As bars are often serious obstacles to navigation, the necessary depth of water is maintained by dredging, which must be constantly repeated, for deposition at that point goes on continuously.

The Mississippi River enters the Gulf by several mouths, called "passes," and the Southwest Pass, which discharges more than half the volume of the river, was so shoaled by the bar that vessels drawing more than 16 feet could not enter. Converging jetties, 4 miles long on one side and 3 miles on the other, and narrowing the channel from 6,000 feet at the upper end to 3,600 feet at the seaward end, were built in 1903–09 and so increased the velocity of the current that deposition ceased and the bar was scoured away to a depth of 35 feet. Above the bars, the river is 200 feet deep. The first improvement was of the South Pass by Captain Eads, whose jetties, built in 1875–79, deepened the channel to 25 feet.

Deltas are accumulations of river deposits at the mouths of streams, built up above the surface of the water into which the stream discharges. The factors which determine the formation of a delta are not altogether clear, but one of them is evidently the presence or absence of a strong tide and another is the existence and rate of a diastrophic movement of the coast. In lakes and tideless seas, almost all streams form deltas, while rivers that empty into the ocean, or into seas with strong tides, do so by means of estuaries, in which the sea encroaches on the land. North American rivers that enter the Atlantic have tidal estuaries, while those that flow into the Gulf of Mexico build up deltas. In Europe the rivers which enter the Mediterranean, Black, and Baltic seas have deltas; Atlantic rivers do not. The Thames and the Rhine empty into opposite sides of the North Sea, and the latter has built a delta, while the former opens by means of an estuary. The great African rivers, the Niger and the Congo, which empty on the west coast, differ in the same way. The Niger has a delta, the Congo an estuary. The combined Ganges and Brahmapootra have an immense delta in the Bay of Bengal, built up in spite of a powerful tide.

If the sea bottom is subsiding faster than the river deposits material, no delta will be formed, but a slow and moderate subsidence is favorable to delta formation. The great valley of California is drained by the Sacramento River from the north and the San Joaquin from the south; turning westward, they follow parallel courses and enter the bay separately. Before the subsidence which submerged San Francisco and San Pablo bays, the two rivers united in a transverse stream, which entered the Pacific through the Golden Gate, outside of which is a submarine delta, as is

revealed by soundings. Here, delta formation has been arrested and the delta entirely submerged by a movement of subsidence.

When a sediment-laden stream flows into the comparatively stationary waters of a lake or sea, the velocity of the current is checked and the greater part of the load is rapidly thrown down. Deposition is much more rapid in salt water than in fresh, for the dissolved salts are electrolytes, which cause the precipitation of the flocculent, colloid particles of clay, which in fresh water remain suspended indefinitely, just as a pinch of alum will clear muddy water in a surprising manner. Such rapid accumulation of sediment obstructs the flow of the river and causes it to divide and seek new channels, especially when in flood, and form a network of sluggish streams meandering over the low flats. The height of the delta is increased by the spreading waters of the river and the growth of vegetation. Though the Mississippi delta is an area of subsidence, two-thirds of its surface is above water at ordinary stages of the river. If it were not obstructed by levees, the river would inundate most of the delta in times of flood, when the unconfined waters would form a lake 600 miles long, 60 miles wide, and with an average depth of 12½ feet.

The sediment of which a delta is made up varies in accordance with the velocity of the stream that made it. When mountains are near the coast, the rivers flowing from them may be so swift as to make a delta of coarse gravel, but not always. The Fraser River of British Columbia, which enters the sea only fifty miles or so from the mountains and has a strong current, deposits gravel in only a few places in the channel and nothing but fine sand and silt reach the sea and are thrown down on the delta.

In a delta three different sets of beds are distinguishable: (1) the *bottom-set beds*, usually composed of fine material, spread out in regular, nearly horizontal layers over the sea-bottom; (2) the *fore-set beds*, which are made up of somewhat coarser sediment, in layers which have a decided, sometimes steep inclination seaward, depending upon the depth of water and abruptness of the slope (the fore-set beds are like the layers of earth shot over the end of an advancing embankment); (3) the *top-set beds*, which, laid on the upper ends of the fore-set beds, as the latter shoal the water, are, like the bottom-set beds, nearly horizontal and, for the most part, of subaërial origin. The fore-set beds usually make up the greater part of the delta's volume, but the other beds cover a wider area.

The characteristic features of a delta are of importance to the geologist, as enabling him to identify them among the ancient rocks of the earth's crust. According to present information and belief, they play a significant part in that crust.

The rate of delta growth is the complex outcome of several varying factors, the quantity of sediment supplied by the stream, the depth of the sea, or lake, at the river's mouth, the power of the waves, tides, and currents to distribute the sediment. The fact that fresh water floats upon salt water prevents a complete and immediate mingling of the two, and a thin layer of fresh water may carry mud far out to sea, though much the greater part of the river's load is thrown down near its mouth. The delta of the Mississippi has an area of 12,500 square miles and advances into the Gulf at the rate of a mile every sixteen years. The combined delta of the Ganges and Brahmapootra measures about 50,000 square miles and is still advancing into the Bay of Bengal in spite of a strong tide. The delta of the Rhone has been built out into the Mediterranean for more than fourteen miles since the beginning of our era. The Italian coast of the upper Adriatic is fringed with delta deposits, which have grown from two up to twenty miles since Roman times. On the other hand, the Nile delta has grown very little in the last 2,000 years, for a strong current along shore carries away the mud and silt.

Partly by the aid of the floating fresh water, partly by wind and tidal currents, the finest sediment is carried far out into deep water. As before mentioned, the submarine delta of the Amazon extends 125 miles out from shore. Débris from the Indus is carried out 800 miles from the mouth of the river and covers an area of more than 700,000 square miles of the sea floor. Though the Congo enters the Atlantic by means of an estuary, which has submerged a rocky cañon, yet the muddy water may be seen 30 miles out to sea. Many more instances might be given to show that river deposits form thick masses near shore and in very thin sheets cover extremely wide areas of the bottom of the sea.

Deltas in lakes do not differ in principle from those laid down in the sea, except in certain matters of detail. Sediment, especially the finer sorts, does not go down so rapidly in fresh water as in salt and is, therefore, spread over wider areas, giving the surface a gentler slope. Lakes are so often in and near mountains that the inflowing streams are much swifter than those which

enter the sea, which have followed, in most instances, very long courses and discharge only the finest material. Measurements of delta growths in lakes have been made chiefly in Switzerland, for the delta of the Rhine in Lake Constance, of the upper Rhone in the Lake of Geneva, and that of the Aar in Lake Bienne.

The combined effects of atmospheric and river erosion and transportation are thus a steady, if very slow, removal of the land. The figures of annual waste, in tons or cubic feet, seem colossal, but not when compared with the total cubic content of the continents and islands. The rate of removal varies greatly in different regions and in different climates; slope and rainfall are the principal determinants, as is clearly seen when the basins of the Mississippi and the Ganges are compared. Taking only solid, suspended matter into account, the amount carried by the former and discharged into the Gulf of Mexico means a lowering of the surface of the whole basin one foot in 4,920 years, while the drainage area of the Ganges is planed down considerably more than twice as fast, one foot in 1,880 years. The difference is due chiefly to climate, for the western portion of the Mississippi Valley is a semi-arid region, while the Ganges heads in a region of exceptionally heavy precipitation.

Under existing conditions of rainfall and slope, the annual waste of all land surfaces is approximately 11,400 cubic feet per square mile, but, almost certainly, this amount was very different in times geologically ancient, sometimes much more and sometimes much less. So far as our information extends, there were periods of higher and more extensive continents than at present, alternating with lower and smaller land areas. There were also great differences of climate, long periods when the whole northern hemisphere was arid, and times of greater rainfall. These differences must have had a profound effect upon the rate of land waste and sedimentation. The present rate must be much greater than the average of past ages.

The Development of River Systems

The classification of rivers is made from several different points of view. One distinction that is universally made, both in technical language and the vernacular, is that between trunk stream and branch, but it is not always easy to decide to which category a

given stream should be referred. Should not the Missouri, for instance, be regarded as the upper Mississippi rather than the river which is so named? In estimating the length of river systems, the combined Mississippi-Missouri length is always the one taken for the great North American system. A second classification is that into marine and continental, rivers that enter the sea and those that do not. The great majority of rivers belong to the marine class, but some very large streams are continental, such as the Volga, which ends in the Caspian Sea. Usually, the continental rivers are small and found only in arid regions, since, for the most part, they flow into saline lakes. This mode of division gives such very unequal classes as to be of little practical value.

A third distinction has reference to the "grain of the country" and is between longitudinal and transverse rivers. Longitudinal rivers are those which flow in courses parallel to the great lines of structure, such as folding and faulting, and are exemplified by the Danube, the Po, the Shenandoah, the Holston, and other streams of the southern Appalachians. Longitudinal rivers may flow for long distances in the same beds of rock, because they follow the lines of outcrop, along which the strata come to the surface, and their course is generally parallel to the main watersheds. Transverse rivers cut across "the grain of the country," transecting the lines of structure and flowing directly away from the principal water sheds. They also flow across the outcropping strata, so that the kind of rock in the channel is continually changing its character. Rivers that run over and through horizontal strata are neither longitudinal nor transverse, for such a country has no "grain."

These and other schemes of classification that might be mentioned have the drawback of dealing only with the present order of things. Geologically speaking, a better method is the genetic one, which seeks to express the mode of development of drainage systems. This scheme cannot always be applied, for lack of knowledge concerning the history of certain rivers, but the cycles of youth, maturity, and old age can always be identified.

Let us imagine a large and entirely new land surface, recently raised above the sea. No such surface is known of extensive areas recently elevated from the sea-bottom, but the imaginary land may serve a useful purpose in explaining the genesis of a river system. Such a land would have no streams and would be drained by sur-

face rain wash, according to the slope or slopes which, it may be assumed, incline toward the sea. The slopes would not be perfectly plane, nor would the rocks composing the new land be completely homogeneous. There must have been slight depressions, in which the rain-water would gather in little rills, and these would cut small trenches, as they actually do on any land surface not protected by vegetation. Such little gullies would be numerous and, as can be experimentally shown, would form a ramifying system ; some of the trenches would be more favorably situated than others, would carry more water, and, therefore, would be more rapidly deepened and widened after heavy rains and converted into ravines. At first, the ravines would carry only storm water and would be dry in the intervals between rains.

While ramifying, or parallel, systems of dry courses were being established, the ground water would form from the rain, displacing the sea water which originally saturated the rocks of the new land. Those ravines which were most rapidly deepened would be the first to cut down to the water table, and springs would be developed along the ravines and these would convert the rain trench into a real stream. As the water table rises and sinks with the seasons of heavy and light rainfall, the new streams would be periodical, until the channel was cut down to a level at which the springs do not go dry, and then the periodical streams would be made permanent. This scheme assumes a pluvial climate and the modifications due to climatic differences need not be taken into account.

If the new land were not a simple slope, but a folded area of undulating, upward- and downward-bending strata, the valleys formed by the downward-bent rocks would be longitudinal and would be separated from one another by the ridges of up-arched beds. The ridges would not be continuous, but offset, leaving gaps between their ends, through which streams may pass from one valley to another, even before the ridges are cut through by encroaching streams. Both of these methods of communication from valley to valley may be observed in the Jura Mountains of northern Switzerland. Thus, in a land newly elevated from the sea, or newly folded, the streams are determined by the new slopes, are consequent upon those slopes, and are therefore called *consequent* streams.

Southern Florida very nearly exemplifies the hypothetical new land, recently upheaved above the sea, though that upheaval

did not take place in historic times. Its streams have all the characteristics of extreme youth, draining their territory very imperfectly; the depressions of the surface are filled with water and become lakes, the great numbers of which in Florida are in extraordinary contrast to the other Southern States, which have almost no lakes at all. The tributaries of a young river are few, much fewer than at a later stage, and the divides between them are low and obscure.

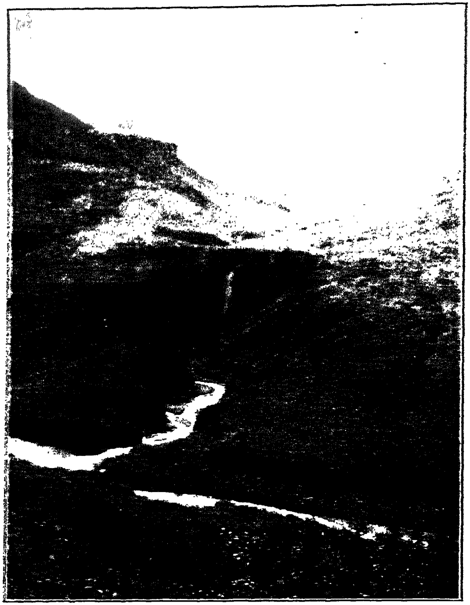

FIG. 120. — Youthful stream and gorge, Cook Inlet, Susitua, Alaska. (Photograph by Capps, U. S. G. S.)

The Red River of the North is a very youthful stream, flowing across an extremely flat plain, the floor of an abandoned lake. On this plain the divides between the streams are so broad and flat that, after heavy rains, the water lies in great, shallow pools, as there is no reason for it to flow in one direction rather than another, for there is almost no slope. In northern Minnesota are the water-sheds between three very different systems of drainage, the Mississippi, the St. Lawrence, and the Hudson Bay; the region is so flat that the streams are sluggish and the divides scarcely noticeable. Although Minnesota and the adjoining regions are geologically very ancient lands, yet their present topography is new, having been molded by the relatively recent

events of the Glacial Epoch, and the streams are, for the most part, in very youthful stages. The Pampas of the Argentine Republic are likewise extremely flat and the government has expended great sums in works to dispose of the rain-water, which otherwise would lie on the surface.

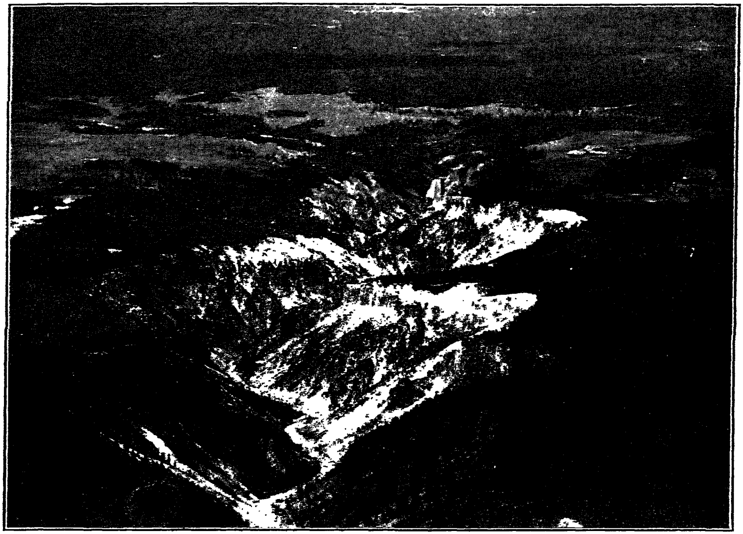

FIG. 121. — Yellowstone Cañon and Lower Falls, from an altitude of 10,000 feet. (Courtesy of the Chief of Air Corps, U. S. Army)

Waterfalls in the main or trunk stream are characteristic of the youthful stage of river development and are caused by the crossing of the channel by hard ledges, the intersection of the stream's course by fault-scarps, lava flows, or similar obstacles. When Niagara Falls were first established, they poured over the great escarpment seven miles below the present site of the cataract, to which the gorge has been cut back. The Falls of Montmorency, near Quebec, are a peculiar case, for the scarp of hard, pre-Cambrian

rock, over which the stream pours, was buried and has been excavated and revealed by the stream itself. However caused, the rock barrier that makes the fall is, in the geological sense, rapidly cut through and the falls disappear, but near the headwaters of the main stream and its branches they may persist almost indefinitely. A reëlevation of the country, which rejuvenates the streams by increasing their slope, will usually bring back the cataracts by reëstablishing the same conditions. This is frequently, but by no

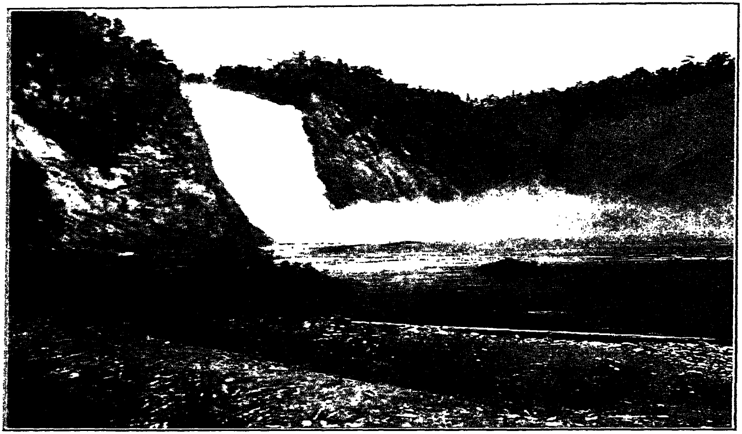

FIG. 122. — Falls of Montmorency, near Quebec.

means always, the explanation of the occurrence of rapids and cascades in old rivers, such as the Delaware and the Potomac.

As the river system matures, the channels are cut down and the larger streams rapidly reach base level, when vertical cutting must cease though lateral widening may continue. The depth of the gorges and cañons is determined by the altitude of the region above sea level. By the aid of atmospheric coöperation, the narrow, river-made gorges are widened into valleys, which, in the case of a large river, may be many miles in breadth. On the sloping sides of the valley, and by a repetition of the conversion of rain gulleys

into permanent streams, new tributaries are established, which are called *subsequent*, because such is their relation to the consequent streams. Certain of these new tributaries flow in opposite directions to the course of the consequent streams and are called *obsequent*. A good map of the mature drainage in a region of pluvial climate shows the really remarkable way in which the streams multiply and ramify to every part of the basin. Few lakes, or none at all, remain in regions of mature river systems; south of the glaciated area in the United States the paucity of lakes is remarkable, with the exception of Florida, a relatively new land.

The adjustment of streams to rock structure consists in the taking advantage by the rivers of every line of weakness in the rocks which facilitates the cutting of the valleys. The weakness may be in lines of soft rocks, of faulting, folding, jointing, any or all of these, and channels are shifted to conform with these lines. When the streams have reached base level, which they do quite rapidly and often before the youthful stage of development has been passed through, the valleys are widened and the streams carry away the material washed in by rain and thus the divides are lowered, so that it may no longer be obvious why a stream flows in a given direction.

In a mature system of drainage the valley surfaces have been so enlarged that the rate at which the land is eroded is accelerated and a greater load of sediment is brought into the trunk stream, and the load is sometimes so great that the lower part of the river is no longer able to carry it all and spreads the excess over the flood plain. The channel of an overloaded stream is raised by its own deposits so as to deflect the tributaries to a course parallel with the main river, from which they may be cut off, so as to enter the sea independently. In northwestern Nebraska the Platte River is heavily overloaded and has built up its banks, while its tributary, the Loup Fork, is diverted to a parallel course, which it follows for many miles before entering the Platte.

The old age of a river system is reached when all the streams are at base level and the area drained by the system has been reduced to a low, featureless plain. The sluggish streams meander in sinuous channels through their own deposits. Meandering is not confined to sluggish streams; any stream flowing in soft materials and in a valley of little slope will meander, as does the lower Mis-

sissippi despite its strong current. When its basin has thus been smoothed down, a river does but little more work, though it will continue to carry fine sediment to the sea. There is much evidence to show that land areas may lie just above sea-level for long ages, undergoing hardly any change, until a new cycle is inaugurated by the elevation of the region.

Cycles are seldom complete, as they are almost always interrupted before the theoretical condition of old age is reached. An elevation of the region may simply rejuvenate the streams by increasing their velocity. On the other hand, the upheaval may be accompanied by warping, folding, or faulting of the rocks, and if so, the drainage of the region may be completely revolutionized. Whether this revolution takes place or not depends largely upon the rate at which the diastrophic movement is carried out. If it is done rapidly, the river system will surely be changed more or less radically; but if very slowly, the streams may be able to cut down through the rocks as fast as these are raised and thus maintain the old courses.

The reëlevation of a region begins a new cycle, whether the preceding one was or was not complete. Depression, on the contrary, ends an old cycle without beginning a new one, for it diminishes or puts a stop to the cutting power of the streams whose lower reaches are "drowned," that is, invaded by the sea and converted into bays and estuaries.

Again, the cycle of certain rivers may be prematurely ended by increasing aridity of climate. The outlet to the sea may be cut off, establishing a new base level, which may either be above the sea, as in the Great Basin, or below it, as in the case of the Volga and the Jordan. The vast floods of lava which overwhelmed the northwestern United States entirely obliterated the old river systems, requiring the establishment of new ones, as did also, for the minor streams, the drift sheet left behind by the retreating ice of the Glacial Epoch. Some of the large streams, like the Connecticut and the Hudson, were entirely occupied by the ice; others, such as the Delaware and the Susquehanna, had their lower courses free and, no doubt, had streams flowing in them during the Glacial Epoch. When the ice melted, the larger valleys remained open and were reoccupied by streams; all the small valleys were obliterated.

Antecedent rivers are those which maintain their courses after a diastrophic movement of upheaval, warping, or folding. They

are antecedent to the movement, and thus a stream which is consequent in one cycle may be antecedent in the next; it may, however, be diverted to an entirely new course and be consequent on a new slope. The simplest case of antecedent drainage is where the region is elevated without deformation and without changing the direction of the slopes. In such a case the streams keep their old channels and merely deepen them further. If a meandering stream be reëlevated by a sufficiently slow movement, so that the velocity of the current be not suddenly and greatly increased, it retains its meandering course while cutting into the underlying hard rock. In such a case the meanders are said to be "intrenched" and a winding gorge with high, steep, rocky walls is the result. Intrenched meanders are an indication of a reëlevated region and an antecedent stream. The valley of the lower Moselle, below Trier, is a deep meandering gorge.

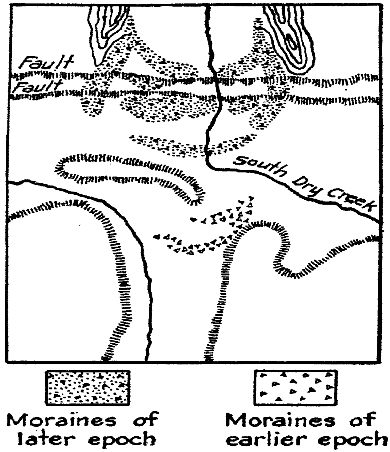

FIG. 123. — Antecedent stream, not deflected by two lines of fault. (Atwood)

In many parts of the world are numerous rivers which seem to have taken the most impossible courses, that is, assuming that rivers have made their own valleys and did not merely take possession of channels made by other agencies. That some rivers are flowing in valleys which they did not excavate is undoubtedly true, but in the great majority of instances the streams have excavated their own courses. These paradoxical rivers are usually believed to be antecedent, but, in some cases at least, there may be a different explanation. One such instance is the Columbia, which is deflected by the great volcanic plateau of that region; it flows southward for some distance and then flows directly at the Cascade Mountains, through which it has cut a great cañon. The explana-

tion is that the river was flowing westward to the Pacific when the Cascade Mountains, a range of very late geological date, began to rise across its path and rose so slowly that the river could cut downward at least as fast and so keep its channel open.

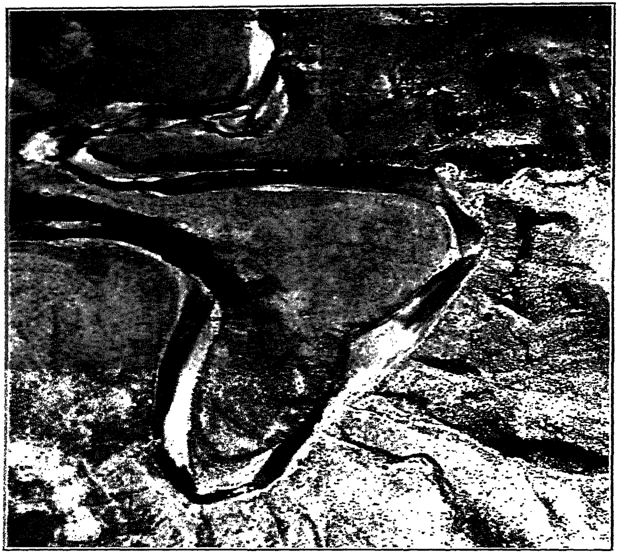

FIG. 124. — Intrenched meander of Salt River, Ariz. (Courtesy of the Chief of Air Corps, U. S. Army)

An even more remarkable case is that of the Green and Yampa rivers, which trench the Uinta Mountains of northern Utah. The Green River, flowing southward, meets the lofty range of which the snowy crests would seem to offer an insurmountable obstacle, but the stream has cut a great cañon, Flaming Gorge, through which it flows to the axis of the range, then turns eastward along that axis to its junction with the Yampa, then turns southward again through the flank of the mountains, emerging on

the southern plain. Not satisfied, so to speak, with this wonderful achievement, the river turns back to the mountains, cuts out a segment, and then takes a final turn to the south, on its way to join the Grand River. The Green and the Yampa are by most observers believed to be antecedent streams, older than the mountains and maintaining their original courses as the range was slowly upheaved across their path.

Such behavior on the part of rivers is not exceptional, but very common, and is exemplified by the large rivers that cut through the Appalachian ranges in their southerly or easterly course to the sea. The Delaware Water Gap is merely the best known of many river gorges through the mountains; the Lehigh Gap, the Susquehanna and Potomac gaps are all of the same nature. These rivers began as consequent streams on a gently sloping plain, formed, as Professor Johnson believes, by the deposits of the Upper Cretaceous sea, which transgressed over the worn-down stumps of the ancient Appalachians. On this assumption, these rivers are superposed. (See *below*.) When they had intrenched themselves, the mountain region was warped upward, the streams cutting down at the same rate. Longitudinal valleys were opened along the strata of soft rock, the hard ones forming the ridges, which are thus not ridges of folding but of erosion. Above and below the gaps, which are cut in hard rock, the valleys are widely open and gently sloping because of the softer rocks which underly them.

The Indus cuts the Himalayas in stupendous gorges, and the southern Andes are trenched by rivers which rise in the Eastern Pampas and go through the Cordillera in cañons, some of which are of greater dimensions than the Grand Cañon of the Colorado. In attempting to explain these remarkable instances of river action, it must be remembered that rivers never flowed uphill, as it sometimes seems necessary to believe that they did. When the rivers began their flow and carved out their valleys, the topography was different from what it is now, and the course which they then took was the one that each was compelled to take by the then existing slopes. It is the modern topography that seems to require the uphill flow.

The fifth category in this genetic scheme of classification is the *superimposed*. An old topography may be completely buried by one or another of the various methods of rock accumulation. The great Columbia River lava plateau of the Northwest was built up

by floods of basaltic lava which, for 250,000 square miles, buried the old topography out of sight, filling the valleys and submerging the hills and forming a raised flat surface. A new system of drainage was established on the plateau, which had no reference to the old topography or its underlying rock structure. Then there is the immense sheet of drift, so often referred to, which covers the northeastern states and the adjoining Canadian provinces and was left behind by the retreating ice of the Glacial Epoch. Innumerable borings have encountered these buried valleys and made it possible to map the pre-Glacial drainage. All over this region, the smaller streams flowed northward to the St. Lawrence, for the Great Lakes were not then in existence.

The surface of the drift had a southward slope and the new system of streams necessarily took that direction and thus were *consequent* in character. The new streams rapidly cut through the incoherent drift and began to excavate channels in the underlying hard rocks, with reference to which they are *superimposed*. The older rocks form an irregular surface beneath the mantle of drift, and the newer streams, except when they happened to coincide, more or less partially, with a buried, pre-Glacial valley, first encountered the more prominent ledges below the drift. These projecting ledges caused rapids and cascades which there has not yet been time to remove.

A very remarkable case of superimposed rivers is afforded by the Gunnison and its tributary, the Uncompahgre, in western Colorado. The two streams began their course upon a westwardly sloping plateau, which was built up chiefly of a very thick mass of an easily removed volcanic ash. The course taken by the Gunnison happened to bring it over the site of a buried granite mountain, and when the channel had been cut down to the granite, it was so deeply intrenched that it could not change its course and was compelled to cut into the hard rock, until it had cut a cañon 2,000 feet deep in the granite. The Uncompahgre flows parallel with the Gunnison for a considerable distance before uniting with it. As chance laid the course of the Gunnison over the buried mountain, it laid that of the Uncompahgre over a buried valley, but it could not excavate below its main stream, which forms its base level. Since the excavation of the cañon, the mountain has been exposed by erosion, and were not the history of the region well known, the course of the river would be utterly inexplicable.

The five classes of streams enumerated, the antecedent, consequent, subsequent, obsequent, and superimposed, are not mutually exclusive, for the same stream may without change of course, at different stages of its history, be referable now to one class, now to another. Even parts of the same stream may be properly referable to different classes, a strange fact which is true because old river systems are usually a patchwork of streams that were originally independent, but have united with one another in the process of adjustment, which, if sufficient time is allowed, becomes surprisingly close. Appearances to the contrary notwithstanding, all streams seek out the line of weakness and take the path of least resistance.

Through the recession of spring-heads (see p. 245), working up-stream, rivers tend continually to lengthen their courses, and this lengthening of streams, together with the accompanying displacement of watersheds, has some very curious results. Two streams, for example, that head on opposite sides of a ridge, with their two valleys more or less in line, may each work backward and actually pass each other without meeting, but opening a pass through the ridge. This has the remarkable result of a continuous valley with two opposite-flowing streams and is not at all a rare phenomenon; it is produced in different ways. In the central valley of Montana, between the Big Belt and Little Belt Mountains, the Shields River flows south and Smith River flows north, with hardly a perceptible divide between them, but this is a longitudinal valley of folding and no ridge was cut through.

The lengthening of streams and their branches and the resultant shifting of divides often have brought about the curious process known as "stream capture," or "piracy," by means of which streams, or, much more commonly, parts of them, are diverted to more favorably situated streams and thus made part of the more successful system. Many anomalies in the courses of streams are thus to be explained. The more favorable situation of a stream may be brought about in various ways, according to the topography and rock-structure of the region involved. The more advantageous condition may be in a shorter course and greater fall, with more rapid current. There is another circumstance which may give the advantage to a stream that would seem to be less favorably situated. Of two more or less parallel streams, flowing at different levels, the lower one would give greater fall to its *tributaries*, though the stream itself has less fall and slower cur-

rent. The tributaries of this lower level stream will work upward, lengthening their courses, and one of them will eventually work its way through the divide and tap the parallel main stream, which will lose all its water above the point of junction. This is because the tapping tributary empties into a main trunk at a lower level.

If two streams rise on opposite sides of a watershed and one of them has a much steeper course than the other, it will work upward faster and ultimately capture the headwaters of the opposite side. Certain streams in the Catskill Mountains exemplify this process.

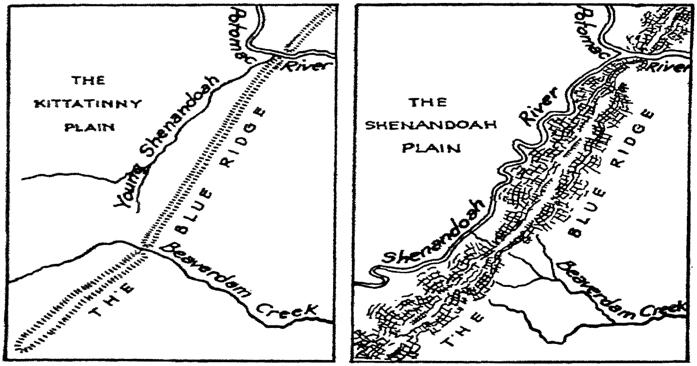

FIG. 125. — Two stages in the development of the Shenandoah River and beheading of Beaverdam Creek. (Willis)

These mountains (really a plateau) have a gentle western slope and, on the east side, a steep escarpment facing the Hudson River. A westward stream, such as Schoharie Creek, flows down the gentle slope with moderate velocity, while such streams as the Plaaters Kill and Kaaters Kill, on the eastern side, flow down the escarpment much more rapidly, have lengthened their courses upstream and captured and diverted several tributaries of the Schoharie. These captured tributaries have a very curious course; they begin by flowing toward the Schoharie, just as they originally did, but each one makes a sharp turn, reversing its direction, and joins the capturing stream. So characteristic is this sharp bend, that it is called the "elbow of capture."

Many of the transverse rivers which cut through the Appalachian ridges exhibit numerous stream captures effected in several ways quite different from those displayed in the Catskill streams. One of these ways is exemplified by the Potomac and Shenandoah rivers and Beaverdam Creek. When the Potomac was beginning to cut its gap through the Blue Ridge, where now is Harper's Ferry, a much smaller stream, Beaverdam Creek, was cutting a similar gorge, Snickers Gap, through the same ridge a few miles to the south. The Shenandoah was then a youthful and short tributary of the Potomac, which it entered from the south, flowing along the longitudinal valley which was beginning to be carved out of the soft rocks to the west of the Blue Ridge. As the Potomac was much larger than the parallel Beaverdam, it cut down its gorge much more rapidly, thus giving a steep and swift course to its tributary, the Shenandoah. The latter extended its length up the valley, until it tapped Beaverdam Creek and captured its upper course, diverting its waters to the Potomac, thus "beheading" it, as is said of a stream which has lost its upper waters. Beaverdam Creek no longer flowed through Snickers Gap, which was abandoned, becoming a dry "wind gap," while the creek took its rise some distance to the east of the ridge. The great number of wind gaps in the Appalachian ridges, which, though cut by streams, now have no water in them, is an eloquent proof of the frequency of stream-capture among the Appalachian Mountains.

An important case of capture is afforded by the upper Meuse and Moselle in France, because it is so well authenticated. These rivers approached each other closely in the neighborhood of Toul. A branch of the Moselle cut through the divide and tapped a tributary of the Meuse, diverting the waters to itself, leaving a sharp elbow of capture, which is still clearly shown. "But only a geological examination of the river deposits can yield a positive proof. This proof has been found in this case: rock débris from the Vosges has been found below Pagny-sur-Meuse and it could also be established that the diversion took place in the Glacial Epoch." (Supan.) The meaning of

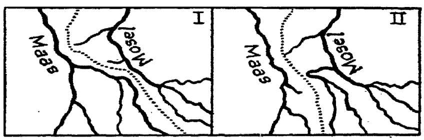

FIG. 126. — Capture of a branch of the Meuse (Maas) by the Moselle. (Supan)

this is that the Meuse, as at present constituted, has no branch coming from the Vosges Mountains, while the tributary diverted to the Moselle rises on the west flank of those mountains. The finding of débris on the bank of the Meuse, which can be identified as having been derived from the Vosges, proves that a connection of the Meuse with those mountains once existed which does so no longer.

It may seem surprising that a river may be cut up in fragments which, nevertheless, continue to flow, but that is because we are apt to think of a stream as a canal which receives all of its water from one end. On the contrary, springs and tributaries feed it along its course and the number and position of those feeders determine how long a segment of a stream may continue to exist. When Beaverdam Creek was beheaded by the Shenandoah, for instance, it lost all that part of its course which ran above and through Snickers Gap, but east of the gap, the creek continued to flow. Very short segments may persist as pools, like the "oxbow lakes" of the lower Mississippi, which are meanders severed by the river's cutting across their necks.

All the preceding instances of stream diversion took place in prehistoric times and are inferred from the present courses of the streams and their tributaries, but several alterations in drainage systems, natural or artificial, have occurred within historic times and have been credibly recorded. The great Hoang-ho in China has frequently shifted its lower course, owing to the raising of the river bed by its own deposits and by breaking through its raised banks; the river has been subject to disastrous floods. The oldest recorded place of discharge into the Yellow Sea is the northern one 39° 4′ N. latitude. From the thirteenth century till 1851, it was farther south at 34° and in the years 1851–53, it turned back to the north and in 1887 broke out again to the south.

Some of the French rivers have undergone remarkable changes in late centuries, as is shown by comparing a series of maps and old documents. In the Department of the Jura the Vallière at present receives four tributaries from the east, the Sorne, Dérobé, Roi, and Sonnette, but in 1658 only the last named emptied into the Vallière, for the Sorne then joined the Sonnette. In 1748, the Sorne became a separate tributary of the main stream and sent out the Roi as a branch. The Dérobé first appears on the map in 1851 and then as a branch of the Sorne, from which it subsequently

separated. (Supan.) How slight a change may cause a permanent diversion is shown by an instance in Ohio. Raccoon Creek originally flowed westward to Pleasant Run, but, as a result of building a mill-dam and race, it turned east to a junction with Rush Creek, which has persisted, though the dam was long ago destroyed. (Tight.)

The Rhine has had an extraordinary series of vicissitudes, resulting in radical changes in course and direction, having, at different times, discharged into the Mediterranean, the Black Sea and, finally, into the North Sea. At a time quite late in geological history (middle Pliocene), but before the human period in Europe, the Rhine was connected with the Rhone through the Doubs and the Saône. At another period the upper Rhine and the Lake of Geneva were connected with the Danube, which then, as now, emptied into the Black Sea. The opening of the rift valley, by trench faulting, between Bingen and Bonn, cleared the way for the river to enter the North Sea. The Biberthal in Switzerland was once occupied by the Rhine, which flowed directly from Schaffhausen to Waldshut; the latter abandoned channel is now used for a railroad.

This list of changes in drainage systems might be greatly extended, did space permit, and this section must be closed with the mention of great river systems in South America and Africa, in which important changes seem to be impending, though not yet effected.

In Africa the tributaries of the Nile and the Congo are very close together, and what may eventually result from this is difficult to foresee. "To the north and northeast some of the swamps forming the sources of the affluents of the Congo and the Nile are separated only by low undulations, in some places no more than fifteen feet wide. In years of extra heavy rainfall, the two river systems may thus be connected, especially as here the rise of the waters is often surprisingly rapid. As a result there are a large number of species of fishes common to both water courses." (Lang.)

In South America the Cassiquiare, a branch of the Orinoco, is connected with the Rio Negro, which flows into the Amazon. The great southern tributary of the Amazon is the Madeira, the headwaters of which are almost connected with those of the Paraguay, and in seasons of exceptionally high water are actually so con-

nected. The Paraguay is a branch of the Paraná, which, by junction with the Uruguay, forms the great Rio de la Plata. It is thus possible to travel by canoe from the mouth of the Orinoco to that of La Plata, a distance of more than 3,000 miles in a straight line. Small diastrophic movements might suffice to bring about great changes in these vast South American rivers.

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CHAPTER XIV

SNOW AND ICE

In the circulation of water, it is necessary to have some means of preventing the indefinite locking up of moisture, in the form of ice and snow, in the polar regions and on high plateaus and mountain tops, above the *snow-line*, or *limit* of *perpetual snow*, which is the level above which all atmospheric precipitation takes place as snow. The altitude of the snow-line is much affected by local conditions, but, broadly speaking, it is determined by latitude. In the tropics the line is 15,000 to 16,000 feet above the sea, descending toward the poles; within the polar circles it comes down nearly to sea-level, but is not known actually to reach that level at any point in the northern hemisphere. The following table, with some omissions, is that given by H. Philipp in meters.

Alps	2400–5200 m	Andes of Ecuador . .	4500–4800 m
Pyrenees	2500–2900	Rocky Mountains . .	3000–4000
Scandinavia	1100–1900	Sierra Nevada . . .	3200–3500
Tian Shan	3450–4000 (?)	Alaska	700–2200
Himalayas	4800–5000 (?)	Francis Joseph Land .	50

The means of restoring snow and ice to the system of atmospheric circulation are various. Direct evaporation is important, especially in very dry regions, for ice evaporates without melting. Avalanches bring down great quantities of snow to levels where it melts, and most effective of all are the glaciers, or streams of moving ice, which descend to levels where melting occurs or into the sea, which breaks off fragments and, as icebergs, transports them to lower latitudes, where they are disposed of by melting.

Avalanches are great masses of snow which descend from mountain tops with very high velocity and produce such extraordinary air pressure that the wind is of dreadful destructiveness. As avalanches follow the same paths, their tracks of devastation are plainly visible as naked scars on mountain sides. Winter avalanches of dry and powdery snow do comparatively little damage,

though they may generate terrific winds, but in thawing weather, when the snow is heavy with water, great masses of earth and rock are brought down by the avalanche, which sweeps everything before it. Though acting only sporadically in time and space avalanches are efficient agents in the transfer of rock and earth from higher to lower levels. On a small scale, snow-slides remove soil, naked and unprotected by vegetation, from steep slopes. In the White River bad lands (see p. 216), and no doubt in other areas also, sliding snow strips off the soil from the steep-sided buttes and exposes fresh surfaces of rock to the action of the rain.

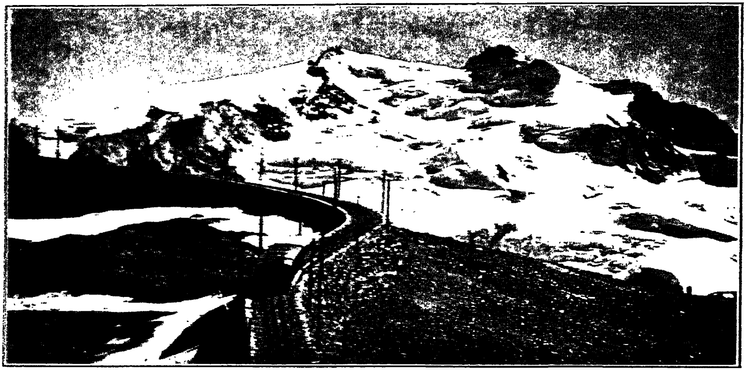

FIG. 127. — Fields of snow and névé on Monte Rosa. (Courtesy of the Swiss Federal Railways)

Glaciers are masses of ice which flow under the action of gravity, as if ice were an exceedingly viscous fluid. Glaciers were first scientifically studied in French Switzerland and the terms there invented have been adopted by English-speaking geologists, just as our terms of vulcanism are mostly Italian. The mechanism of glacier flow is a much disputed physical problem that cannot be dealt with here. It must suffice to say that the movement of ice in a glacier is not a glide, as snow slides off a roof, but a flow. Of all forms of ice, much the most important, geologically speaking, are glaciers, though at the present time their contributions to the sum total of rock destruction and reconstruction are relatively

small. On the other hand, from the point of view of historical geology, the careful study of existing glaciers and their characteristic mode of action is of the utmost importance. By learning to identify their former traces, it has become possible to state that in the past history of the earth there have been repeated epochs or periods, when glaciation took place on a vast scale, when the ice-fields measured millions of square miles over regions where, to-day, there is nothing of the kind to be found.

Naturally, the latest of these "ice-ages" is that which has left the clearest and most extensive evidence of glaciation, as it came to an end only a few thousand years ago, long after Man had appeared in Europe. This was in the Pleistocene epoch of the Quaternary age. Back of that, in the latter part of the Palæozoic era, in the Permian and Carboniferous periods, there was a vast development of glacial fields in the southern hemisphere, in Australia, South Africa, and South America, and, on a much smaller scale in the northern hemisphere, in India and North America. Devonian (?) glaciation has been shown only in South Africa, Cambrian in China and Australia, and pre-Cambrian in Canada, South Africa, and, perhaps, in China. These geographical limitations are, assuredly, far too narrow, for the destructive processes of erosion must have removed all evidence of ice-action from great areas, where it formerly existed. The wonder is that so much should have been preserved.

The present is a time of glacial retreat; in Alaska and Switzerland and Greenland, the glaciers have retreated in the last century and there is evidence of a progressive desiccation in regions so widely separated as California and Central Asia within the historic period. These facts all show the necessity of learning everything that can be discovered concerning existing glaciers and the amount and manner of their work as dynamical agents.

We have first to learn the method of glacier formation and the factors which determine the presence or absence of glaciers in any given region. Glaciers are composed of ice which has been made from snow, and the first problem, therefore, is to determine how snow is compacted into ice. Both are composed of the exquisite hexagonal crystals with which every one is familiar, but in ice they are in physical contact, which produces a colorless transparent body, while in snow they are intimately mixed with air. The intimate mixture of a gas with a transparent solid or liquid causes

whiteness and opacity. Powdered glass, or salt, or any other transparent material is opaque and white, though, under the microscope, each particle is seen to be without color and transparent. To convert snow into ice, therefore, it is necessary merely to expel the air and bring the crystals into contact; to effect which change pressure alone is insufficient. Above the snow-line, on a mountain top, the snow falls in a dry, powdery condition and at a temperature considerably below the freezing point. The summer sun melts some of the surface snow and the water so formed trickles down into the cold snow beneath, expelling the air or causing it to form bubbles. Then the water refreezes, producing a material for which there is no English word and the French term *névé* is therefore used (in German *Firn*). Névé is intermediate between snow and ice and is composed of small spherules of clear ice, but the abundant bubbles of air make the mass opaque. Increasing pressure of continually added snowfall expels a large part of the air and converts the névé into hard ice, though much glacier ice remains white and opaque from the air-bubbles retained in it. The glacier is composed of ice which grades upward imperceptibly into névé and begins its flow down its bed or channel.

The structure of glacial ice is characteristically different from that of pond-ice. The latter is made up of parallel crystals with their optical axes perpendicular to the surface of the water. Glacial ice consists of crystalline grains, which increase in size toward the lower end of the glacier and with the optical axes irregularly arranged. The banded structure of a glacier, which has caused so much discussion, especially the blue bands of clear ice, was formerly believed to be due to successive snowfalls on the névé, but is now referred to the shearing planes, along which the ice parts and which run obliquely upward and forward from the bottom. "Late investigations by Hamberg and Philipp bring the banding into immediate relation with the processes of motion in the glacier. Accordingly, the blue bands would be the refrozen shearing fissures" (Philipp) along which water gathers.

The temperature within a glacier would seem to follow different laws in temperate and in polar lands. Measurements made in Alpine glaciers show that, at every depth, the temperature corresponds to the melting point of the ice for the pressure at that depth, and only at the surface is the glacier subject to seasonal changes. Pressure lowers the melting point of ice and changes of

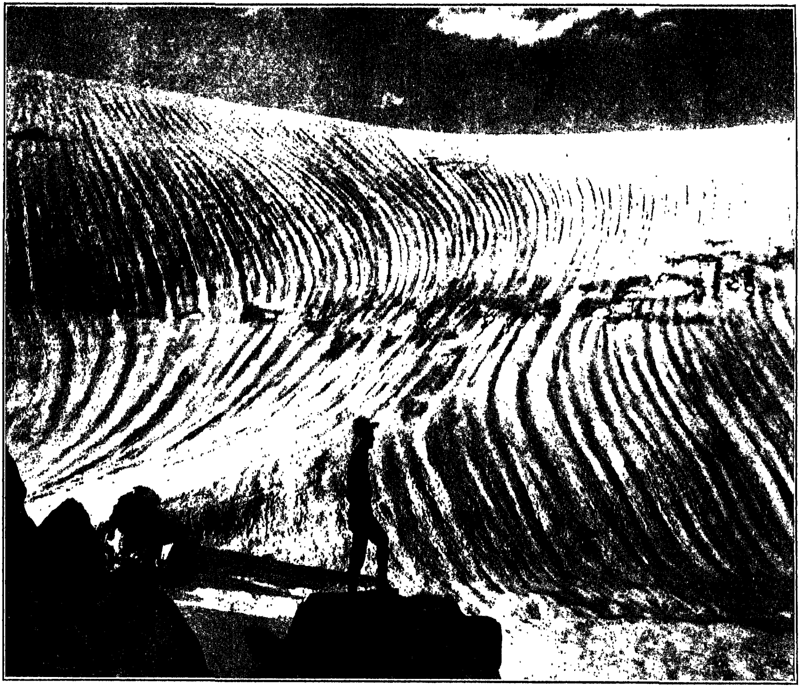

Fig. 128. — Grasshopper Glacier, Beartooth Mountains, Mont., showing lines of flow. (Photograph by Brown, St. Paul, Minn.)

pressure within and at the bottom of the ice cause melting and refreezing without any change of temperature. Measurements made in the inland ice of Greenland at an air temperature of — 40° F. showed 7° F. at a depth of 85 feet in the ice. The extrapolated temperature curve would indicate that the melting point would not be reached above 675 to 1,000 feet. This method of converting snow into ice explains the geographical distribution of glaciers, which must be formed where more snow falls in winter than is melted in summer and the increasing mass of snow cannot be disposed of by avalanches, melting, or evaporation. Polar lands and high mountains, in climates that are not too dry, are the seats of glaciers. The Rocky Mountains south of Idaho have no glaciers except a few small remnants, while in Canada and Alaska there are magnificent glaciers. The snowfall increases and the snowline descends northward. Glaciers are few and small within the tropics, because the limit of perpetual snow is so high that only small areas of land rise above it, as mountain peaks, and also because of the slight changes in temperature, which are hardly enough for alternate thawing and freezing.

The most important factor in determining the presence or absence of glaciers is the temperature of the air, a temperature which must take into account the summer as well as the winter. Northern Siberia, where the winter cold is extremely severe, has no glaciers, for the snow all melts in summer. The vast inland ice of Greenland is supplied by a very limited snowfall, because on the high interior plateau there is practically no loss by melting. The United States Rockies might have glaciers if the snow were much heavier or the summer colder.

The movement of a glacier is in many, not all, respects like that of a river of extreme viscosity, and the motion of the ice, like that of water, is differential, some parts moving faster than other parts. By planting a line of stakes across the glacier and observing the daily changes in the position of the stakes with a transit, it has been proved that the middle of a glacier moves faster than the sides, which are retarded by friction with the rocky banks. In a few favorable situations, as where the ice flows past the narrow mouth of a gorge without entering it, thus exposing much of the thickness, it has been possible to fix a vertical line of stakes in the ice, which show that the top of the glacier moves faster than the bottom, which is retarded by the friction of its bed, or "*ice pave-*

ment." The line of swiftest motion is in the middle of the glacier's surface only when the ice pursues a straight course; when flowing around a curve, the convex side moves faster than the concave, which is also true of a river. When the channel is narrowed, the ice moves more rapidly through the narrows and more slowly above and below them; water acts in the same manner.

Under pressure, ice acts like a plastic substance, but when subjected to tension, it is usually very brittle. Not always, for a slab of ice, supported only at the ends, will bend under its own weight, stretching the convex lower side. When the rocky bed of a glacier changes its slope from a less to a more steepened grade, a salient angle is formed and the ice in flowing over that is subjected to tension which causes it to crack across its width, thus forming a *transverse crevasse*, which rapidly widens to a yawning chasm. Below the line of rupture the crevasse is healed, the walls coming together and freezing solid. Ice has a remarkable property of *regelation*, by virtue of which two surfaces of ice, when brought into contact, will freeze together, whatever the temperature of the surrounding medium. Two pieces of ice, floating in hot water, will unite when they touch. Many of the curious phenomena displayed by glaciers are due to regelation. A crevasse appears to be stationary, because, like an eddy in a stream, it is continually reformed along the same line.

A second set of crevasses are the *marginal* ones, which form on the sides of the glacier; they are due to the more swiftly moving middle pulling away from the retarded sides. The ice yields and cracks at right angles to the line of stress and thus the marginal crevasses point upstream at angles of about 45°. When a transverse crevasse is connected with a marginal one at each end, as usually happens, a curved crack, with concavity facing downstream, is the result, and these misled Agassiz into believing that the sides of the glacier moved faster than the middle, which it has a very deceptive appearance of doing. Crevasses, as will be seen later, play a very important part in the economy of the glacier as an agent of erosion and, especially, of transportation.

While necessarily having its source of snow supply above the snow-line, a glacier may descend many thousands of feet below that line. Alpine glaciers descend to 2,000 feet above sea-level, and in New Zealand the glaciers end in subtropical forests of tree ferns. The rate of glacier motion in the Alps is from two to fifty inches a

FIG. 129. — Gorner Glacier and Breithorn. (Courtesy of the Swiss Federal Railways)

day and many times that in the great glaciers of Greenland, which descend through mountain passes from the inland ice. In the latter, the movement is slower. The lower end of a glacier seems to be stationary and is at the point where the rate of melting and the rate of motion balance. A series of hot, dry years causes

the glaciers to retreat and a succession of cool, moist years makes them advance. In temperate latitudes the end of the glacier is an ice arch, or cave, from which issues a stream of water.

The surface of a glacier begins to melt as soon as it descends below the snow line and the bottom melts also from the warmth of the earth. The thickness of the ice thus diminishes downward to the end and material which has been carried along within the ice, gravel, and sand that have been washed into the crevasses and accumulated there, are all brought to the surface in a process which is called the "self-cleansing" of the glacier. On the stagnant border of the great Malaspina Glacier, at the foot of the St. Elias Alps, in southeastern Alaska, the ice is quite buried from sight by the débris which has covered the surface and a considerable growth of vegetation has taken root upon it.

As it is necessary to give names to the various types of bodies of water that are found upon the earth, it is equally necessary to do likewise for the bodies of ice. As Professor W. H. Hobbs has shown, there are two strongly contrasted types of glacial bodies of moving ice upon land surfaces. Frozen sea-water, the pack-ice of polar seas, is here left out of account altogether. The terms used in the classification of glaciers are, as is so lamentably often the case, differently employed by different writers. Hobbs names the two classes (1) mountain glaciers and (2) inland ice, with (3) ice-caps intermediate in character between the two.

Mountain Glaciers (also called valley, or alpine glaciers) are the analogues of rivers, sometimes of lakes, and rocks project above their highest levels, frequently also above the ice-surface, for their whole length. Glaciers of this class head in *cirques*, or rocky amphitheaters, which serve as gathering ground for great masses of snow. There are some exceptions to this rule, as in the case of *hanging glaciers*, which do not always flow out of a cirque, and in a few instances, the crater of a volcano with one wall broken down serves as a cirque. Professor Hobbs recognizes fourteen divisions and subdivisions of mountain glaciers, but most of them it will not be necessary to consider for the purposes of this book.

Nivation. The origin and development of the cirque long remained unexplained until a solution of the problem was suggested by Messrs. F. E. Malthes and the late W. D. Johnson, of the U. S. Geological Survey. The inception of a cirque is by a process which Mr. Malthes has called *nivation*, which means that snowbanks

on high mountains without motion deepen any slight depression in which they lie and cut back into the mountain slope by excessive frost action in summer. The margins of such a snow bank are melted by the sun and saturate the rock around them with water; at night this water freezes and shatters the rock eventually into small particles which are carried down by the snow water. In this manner, a depression is enlarged until an incipient cirque is formed, and if the snow supply is sufficient, a small glacier will be the result. Once established, the cirque recedes and enlarges by a process of sapping.

FIG. 130. — Glacier in cirque, Coast Range, southeast Alaska. (Photograph by Buddington, U. S. G. S.)

Between the stationary and the moving part of the snow in the cirque is a crevasse which runs parallel with the rocky wall of the cirque and, for want of an English term, is called the *Bergschrund*, a German word meaning the mountain gap or crevasse. On the small glacier of Mt. Lyell in the Sierra Nevada, Mr. Johnson was lowered into the *Bergschrund* for 150 feet and found an exposed rock floor, with rock extending to a height of 20 feet on the cliff side, a shelf on which the snow rested. Melting was in process in the crevasse, and the floor of the glacier, elsewhere covered, was here exposed. Both floor and cliff, kept continually wet, and freezing at night, were in active disintegration, which tended steadily to enlarge the cirque. In winter this action ceases and the *Bergschrund* fills with snow, to reopen in the following summer.

Piedmont Glaciers. While most of the many subdivisions of mountain glaciers that have been adopted by investigators need not be considered, something should be said of the piedmont type, because of its importance in Pleistocene times. These ice-bodies are the analogues of lakes and are formed, as the name indicates, on a plain at the foot of a mountain range, by the coalescence of several descending streams of ice. At the present time such ice-lakes are rare and are found only in Chile and Alaska. In the latter region the great Malaspina Glacier and its two neighbors, the Bering on the west, and the Alsek, a much smaller one, on the east, are famous and well-studied examples of the piedmont glacier. The Malaspina, in particular, is typical. In the Pleistocene ice age, piedmont glaciers were very much more numerous and important; their determinable traces are still to be seen at the foot of the Rockies, the Alps, and other ranges.

Erosion by Mountain Glaciers. This is one of the geological problems concerning which there is much debate, some observers contending that a glacier protects the underlying rock from erosion and others considering glaciers extremely efficient agents of denudation. The latter is the view here adopted and, whichever opinion may turn out to be true, there are certain characteristic features found in all glaciated regions, and not elsewhere, however these may have been brought about.

1. *Erosion of the Upland.* In high mountains that support active glaciers, there are two areas to be considered, in which the work of erosion is entirely different. In the mountains above the level of the névé, the agents of destruction are frost and snow and the result is an extreme ruggedness of topography. Cirques are established around each mountain mass and cut back until they are separated only by narrow crests and spines of rock, while all exposed rock surfaces are riven and torn by the action of frost. In certain of the western mountains, where even in the ice age of the Pleistocene the snowfall was relatively limited, such as the Bighorn and Uinta ranges, the steps in the development of the "high level topography" (Hobbs) may be readily followed and then compared with such ranges as the Sierra Nevada, in which glacial maturity is reached.

Concerning the Sierra, Johnson says: "The summit upland — the preglacial upland beyond a doubt — was recognizable only in patches, long and narrow and irregular in plan, detached and vari-

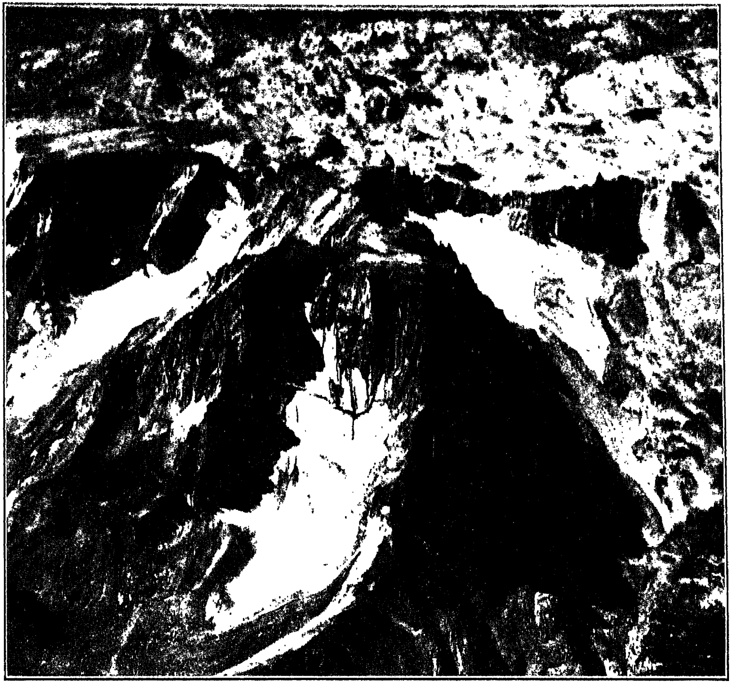

Fig. 131. — Cirques cutting into the upland, Beartooth Mountains, Mont. (Courtesy of the Chief of Air Corps, U. S. Army, 15th Photographic Section)

ously disposed as to orientation, but always in sharp tabular relief and always scalloped. I likened it then, and by way of illustration can best do so now, to the irregular remnants of dough on a biscuit board after the biscuit tin [*i.e.*, cutter] has done its work."

Strictly speaking, this erosion of the upland is not glacial, but it is inseparably associated with glaciers, for it involves such

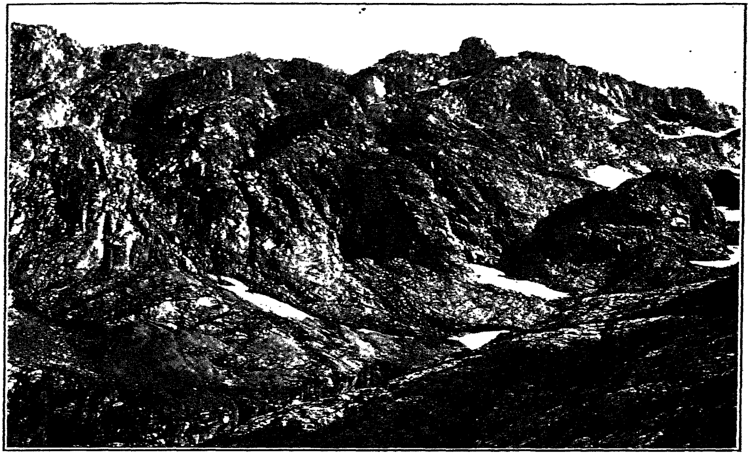

FIG. 132. — Ben Nevis, Scotland, showing contrast between ice-smoothed valley bottom and rugged cliffs above. (Geol. Surv. Grt. Brit.)

accumulations of snow as must form glaciers. The extreme ruggedness of the Alps is due to such intense glacial activity that no remnants of the summit upland remain.

2. *Erosion below the Névé Fields.* This is the series of processes and results which is ordinarily understood by the term of *glacial erosion.* As in the destructive work of a river, the most important factor is the velocity of the current, in a glacier it is the thickness of the ice, which constantly diminishes toward the lower end. The glacier may thus erode actively in one part of its course and not at all in another, as a river does. It is not surprising, therefore, that the foot of an advancing glacier, where the ice is thinnest, has

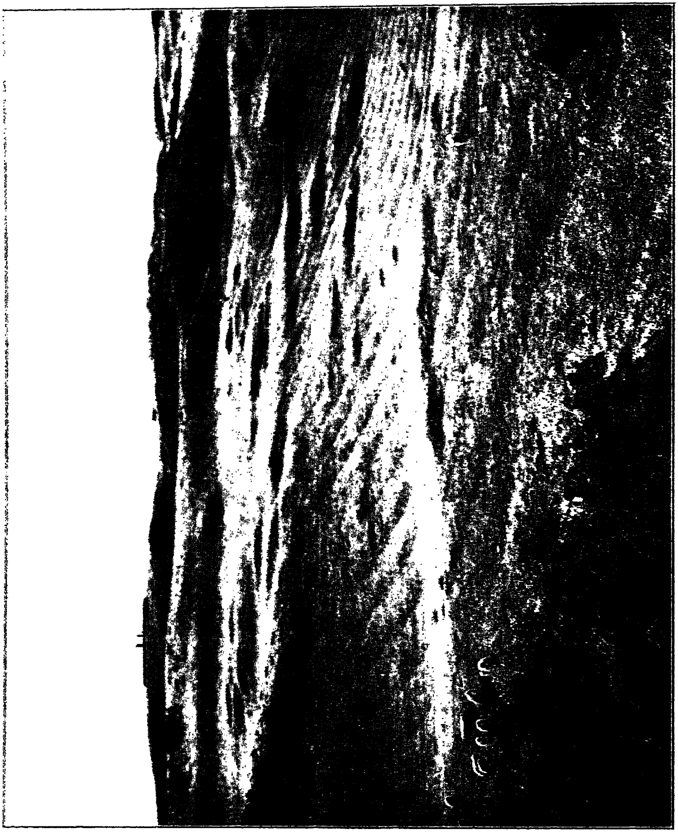

FIG. 133. — Braid Hills, Scotland, ice pavement of Trachyte. Movement of glacier from right to left.
(Geol. Surv. Gt. Brit.)

been seen to override loose gravel without moving it. Except in very high latitudes, cliffs and peaks rise above the level of the ice, and frost-made talus is discharged upon it, some of which finds its way to the bottom through the crevasses. The ice, too, picks up joint-blocks from the bed-rock, a process called *plucking,* and carries them along. The smaller and more separate the joint-blocks, the more rapidly and effectively is the plucking performed, and it is much facilitated by the melting and refreezing which continually go on, due to differences of pressure.

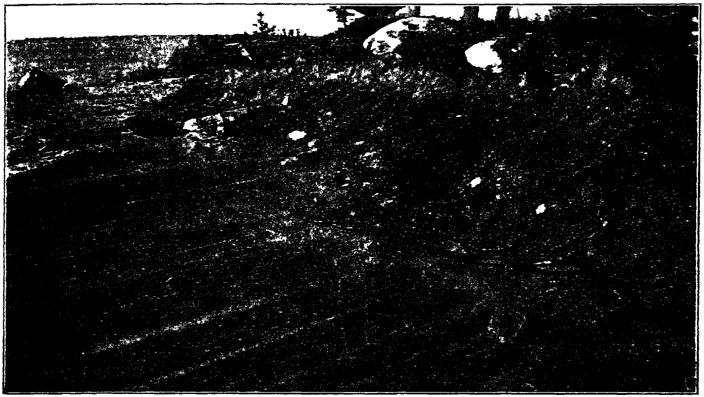

FIG. 134. — Glacial striæ on limestone, overlaid by drift, Pillar Point, Lake Ontario. (U. S. G. S.)

In these various ways great quantities of débris are frozen in the bottom of the ice and wear down the bed by abrasion. Abrasion produces the extremely characteristic rounding, smoothing, and polishing of the rocks over which the ice has flowed, and the rock fragments, held firmly by the immense weight of the ice, are pushed over the bed-rock and cut grooves in that rock corresponding to the size of the cutting fragments, from the finest, hair-like scratches to furrows a yard or more in depth. These *striæ,* of course, take the direction of the ice movement and are parallel for considerable distances, as the teeth of a harrow make parallel fur-

rows. Hummocks of rock over which the ice has moved are smoothed and rounded into the shape called "roches moutonnées" with the upstream, or *stoss* side, gently sloping and polished, the downstream, or *lee* side, abrupt and often rough, as the ice exerts

FIG. 135. — Ice pavement passing beneath Dwyka Tillite, Permian of South Africa. (Gift of Prof. R. B. Young)

no back pressure on that side. When flowing down a rocky valley, or gorge, the glacier grooves and polishes the sides as well as the bed. Figure 136 shows the sandstone wall of the Delaware Water Gap and displays the characteristic glacial modeling. A rock wall, lately abandoned by the Grindelwald Glacier, in Switzerland, is remarkably similar. (H. Philipp.)

The abandoned glacial valley, below the level to which the névé field formerly extended, is not graded to one uniform slope, as a mature river valley is, though perhaps broken by occasional waterfalls. It consists of a succession of steps, of which the treads are hollowed out to form rock basins and the risers are abrupt ledges, which run across the valley, the whole forming the "*cascade stairway*," the basins often occupied by lakes. The risers are partly due to plucking, which leaves an abrupt upstream face, partly to joint planes, often to the incoming of tributaries, which deepen

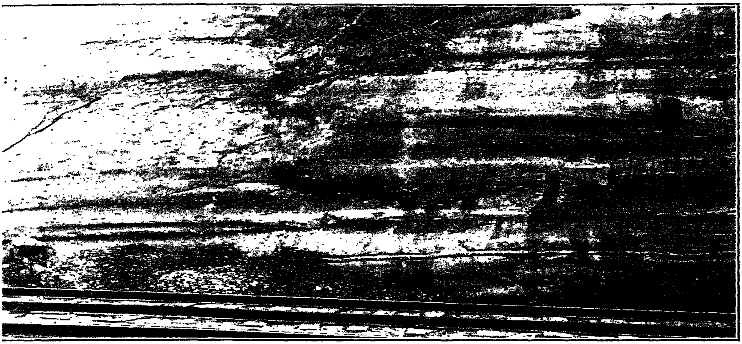

Fig. 136. — Glaciated sandstone cliff, Delaware Water Gap, Penn.

the main glacier and give it increased abrasive power. The highest of the risers is that at the foot of the cirque, so high that an ice-fall once marked its source.

There are a number of dynamic agencies which produce polished and striated surfaces sometimes deceptively like glacial action, but never on more than a very restricted scale. Coast ice, freezing on a rocky shore, and moved back and forth by tides and storms, polishes and striates the rocks, but only in a narrow band. A stream of volcanic mud, carrying blocks or bombs, may produce a similar effect on a valley floor, but not for any great length, or width. "Slickensides," the polished and striated faces of a fault, in which the rocks have been ground against each other with tremendous force, might lead the observer to think them of glacial origin, did not their mode of occurrence preclude such an explanation.

Not only are rocks polished and striated by glacial action, but the larger topography of a glaciated region is molded in a highly characteristic fashion. A river-made valley that has been taken possession of by a glacier is remodeled as follows, provided that sufficient time shall have elapsed.

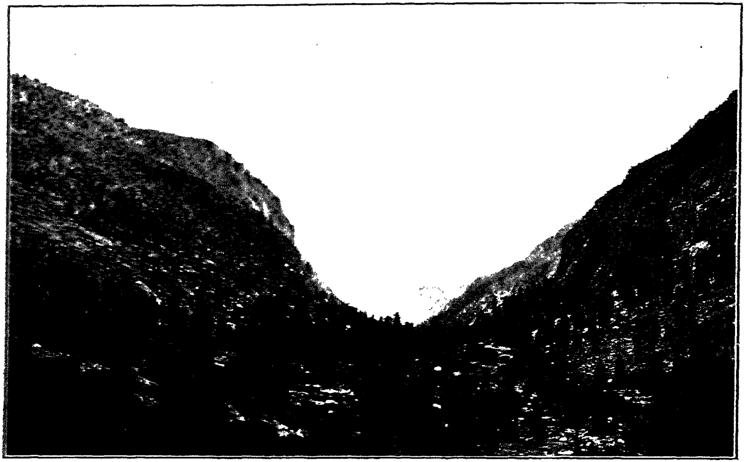

FIG. 137. — Kern Cañon, Calif., U-shaped glacial valley. (Photograph by Gannet, U. S. G. S.)

(1) In cross-section a glacial valley is U-shaped, with broad bottom and steep sides. If the valley was not filled up by the ice, the slopes may be gradual down to the former level of the glacier's surface, where they become abrupt.

(2) Glacial valleys are often straight and open for a long distance; they may have spurs alternating from opposite sides, but the spurs have been truncated by the ice, thus straightening the channel.

The valley may be gently sinuous, as is the S-shaped course of the Delaware above the Water Gap, but this is occasioned by the unequal hardness of the rocks through which the valley is cut.

(3) The tributary valleys do not enter the main valley at grade, as streams of water do, but high above the flow of the latter and hence are called *hanging valleys*. This is because the rapidity of glacial erosion is chiefly determined by the thickness of the ice

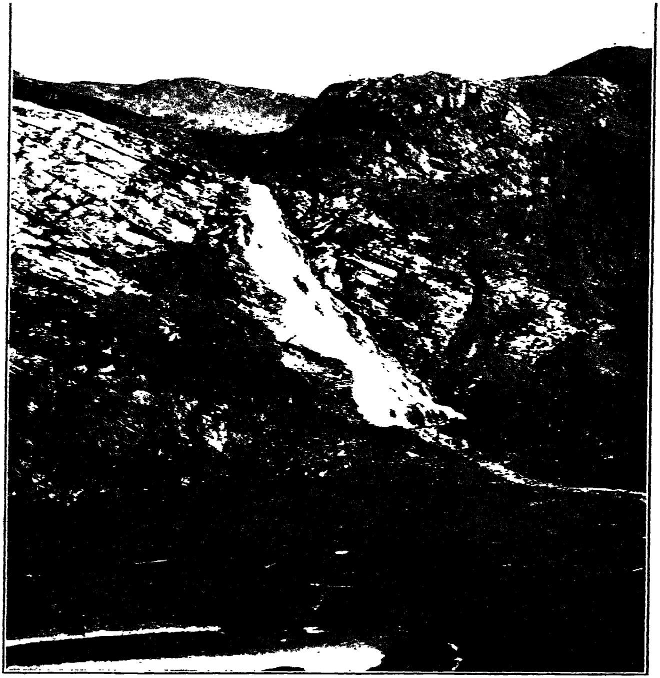

FIG. 138. — Hanging valley, Glen Nevis, Scotland. (Geol. Surv. Gt. Brit.)

and therefore the main valley is deepened much more quickly than the tributary valleys. The accordance of a glacier with its tributaries has to do with the surface of the ice (for the direction of ice movement is determined by the slope of its *upper* surface),

and not with the beds. Hanging valleys may be produced in other ways, but the great majority of them are of glacial origin.

Finally, glaciers, unlike rivers, have the power of excavating their valleys below sea-level, a process which is called *overdeepening*, for the ice must continue its erosive work even after it has entered the sea, its activity diminished by the buoyancy of the water and progressively lessened as the ice is submerged, until it begins to float. On a slowly rising coast, there is no limit to the excavation, as is also the case with rivers.

A remarkable feature of certain glaciated coasts is seen in the *fiords* (or fjords), which are so celebrated in the scenery of Norway. Fiord coasts occur in the high latitudes of both hemispheres; in the northern hemisphere the limit equatorward is latitude 49°, and in the southern 41°, almost always on the western side of land masses. Norway, Scotland, Greenland, Alaska, British Columbia, southern Chile, and New Zealand have typical fiord coasts. Fiords are inlets from the sea, long, narrow, branching, and usually very deep. The bottom, in most instances, is made up of a rock-basin, or several such basins, and is usually deeper in the middle of its course than at the seaward end. Sometimes they are continued along the sea-bottom as submarine valleys. Landward the fiord ends in a river valley, which in Norway, Greenland, and Alaska are still occupied by glaciers.

Though not free from difficulties, the most satisfactory explanation of fiords is that they are valleys, originally formed in any way as by faulting, or river action, but molded and overdeepened by glaciers. The rise of the sea and depression of the land which took place at the end of the Glacial Epoch have added to the depth of these valleys.

A large glaciated region is characteristically different in appearance from adjoining unglaciated areas. In North America an irregular line, which marks the last extension of the great ice sheets of the Glacial Epoch, has been traced all across the continent from Nantucket to the mountains of British Columbia. North of that line, except in the lowlands of Alaska, the country is in remarkable contrast to the areas south of it. In part, the difference is due to glacial deposits, the low hills and winding ridges of gravel, the sandy plains, etc., but glacial erosion has produced the rounded, flowing outlines of the hills and the absence of steep, abrupt cliffs and crags such as abound to the south of the line.

Another great difference between the two regions is in the number of lakes. Canada, New England, the northern parts of New York, and the Middle West have thousands of lakes, while, with the exception of Florida, which is a sea-bottom, uplifted at a relatively late time, very few lakes are to be found in the South. When Sir Charles Lyell visited the United States in 1841, he was surprised by the paucity of lakes in the Appalachian Mountains, in such contrast to the mountain regions of Europe, Scotland,

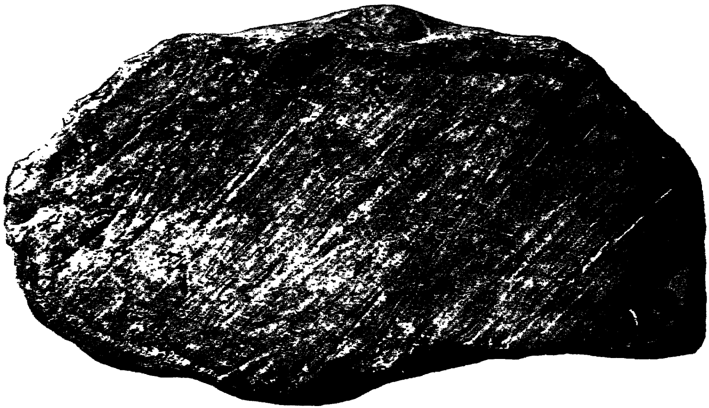

FIG. 139. — Glacial pebble. (U. S. G. S.)

Scandinavia and the Alps. Agassiz's glacial theory had then just been put forth and had found but little favor, so that Sir Charles did not associate the absence of lakes with the non-glaciated mountains.

As in the case of a river, the abrading material is itself abraded, and much of it is ground up to the fine powder which loads the streams flowing from glaciers and gives them the turbid, milky appearance that all visitors to Switzerland have noticed. The pebbles and cobble stones that are pushed along beneath the ice are not rolled over and over and so are not spheroidal, but subangular and sometimes faceted, with smooth faces that meet at an angle. This peculiar shape is due to the shifting or turning

of the stone in the ice; after one side has been worn flat, another is so worn, and this process may be repeated several times. In addition, the glacial pebbles are often striated, smoothed, and polished like the ice-pavement over which they have been forced.

The part of a glacier which descends below the snow-line is subject to summer melting and streams and lakes are established upon the upper surface of the ice. When the ice is broken by crevasses, as it is in almost all mountain glaciers, the surface streams, after a longer or shorter course, are engulfed in these

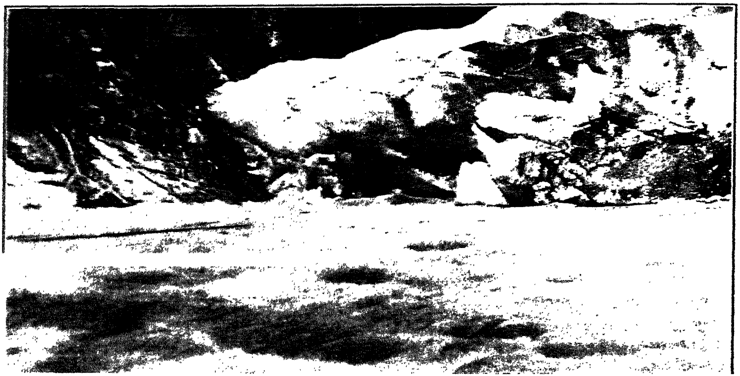

FIG. 140. — Baird River flowing from beneath Baird Glacier, Thomas Bay, southeast Alaska. (Photograph by Buddington, U. S. G. S.)

cracks, in which they melt cylindrical shafts, which in Switzerland are called *moulins* (mills). The shaft may reach to the bottom of the ice, in which case a pothole is cut in the bed-rock by rotating stones, as previously explained. More frequently the moulins do not reach the bottom of the ice directly, but turn aside into horizontal tunnels, through which the water flows, eventually joining the subglacial stream.

Under the great Malaspina Glacier of Alaska are innumerable water courses, which flow out from under the ice as considerable rivers. Some are under such pressure that they issue as veritable fountains, spouting ten feet or more into the air. The ice cap of

Spitsbergen has surface streams which flow for long distances, because they do not enter crevasses.

Glacial Transportation. Rock débris is carried upon, within, and underneath the ice, and the great difference between transportation by rivers and by glaciers is that, in the latter, there is no relation between the velocity of movement and transporting power. To the ice everything is a floating body and fine dust and thousand-ton blocks are carried along together. The material in transit and that deposited are called by the general name of *moraine.* On the surface of the ice the débris is derived chiefly from the overhanging cliffs, from which it is riven by frost. The masses of blocks and stones of all sizes that form a talus heap along the sides of the glacier form the *lateral moraine* and are carried along by the movement of the ice.

Very puzzling, at first sight, is the *medial moraine,* of which there may be one or several. A medial moraine is a long regular line of rock débris in the middle of the glacier's upper surface, separated from the lateral moraines by broad bands of clear ice. The mystery is at once explained by tracing the ice stream upward toward its source, when it is seen that the medial moraines are the laterals of the branches and tributaries which coalesce with those of the main trunk. The number of branches can be told by the number of separate lines of medial moraine. Not quite all of the medial moraine material is to be accounted for in this manner, for some of the rock material picked up from the bed, especially if a hard ledge projects above the rest of the bed-rock, is pushed upward along the shearing planes and makes its appearance on the surface, when this is lowered by melting.

Glacial boulders included in the surface moraines are not worn by the ice, yet they are very generally rounded in greater or less degree. This is the effect of the atmospheric attack and common to all sorts of separate blocks which are exposed to weathering. As was shown in the chapter on the atmosphere, joint-blocks, even when buried in the soil, tend to lose their angles and take on a rounded form, because the corners of a block are attacked from three sides at once and are thus worn away more rapidly than the faces. When the rounded shape has been acquired, weathering is retarded. The blocks in the surface moraines are exposed to atmospheric action for many years before they are finally deposited in the terminal moraines. A boulder might lie on one of the

Fig. 141. — Gorner Glacier, with medial moraines. (Courtesy of the Swiss Federal Railways)

relatively short Swiss glaciers for forty years or more and at an altitude where frost destruction is very rapid.

The *ground moraine* is the mass of rock material and débris of all sizes which is pushed along beneath the glacier or frozen in its bottom. Much of this débris is plucked from the bed, some comes from the surface of the ice, washed down into crevasses and *moulins* and the finer stuff is the product of glacial abrasion, the transported pieces being crushed against the bed-rock or against one another. The rock flour which results from this grinding is mechanically subdivided, but not chemically decomposed. How much of the ground moraine may come to rest beneath the ice is an unanswered question, but it is evident that near the termination of the glacier where the ice is thin, there is some accumulation.

FIG. 142. — Projecting ledge of rock in bed of glacier supplying débris, which works up to the surface along shearing planes. (Hobbs, after Chamberlin)

Under thick ice, abrasion is going on too actively to permit loose material to lie, but when abrasion ends and accumulation begins cannot be told because the bottom is hidden by the ice. In principle the action is the same as in a river which excavates its channel in one part of its course and builds it up in another.

Some débris is transported within the ice and this is called *englacial drift*, which, in quantity, is relatively small. Fine material, dust, and even sand is blown upon the surface of the névé and there buried under successive falls of snow. Further, as was mentioned above, a certain amount of débris is worked up from the bottom along the shearing planes, but there is reason to believe that this is confined to the lower hundred feet or so in the thickness of the ice. Though not great in amount at any given time, in the long course of geological ages, englacial drift must make an important contribution to the totality of glacial deposits.

Transportation by Glacial Streams. In summer time, streams of water, from the melting of the ice, run upon, within, and beneath

the glacier and the subglacial streams persist through the winter, being warmed by the ground and sheltered from the cold atmosphere by the ice. The surface streams differ from ordinary rivers merely in flowing in an ice channel and therefore have little opportunity to pick up débris, but the englacial and subglacial streams are in a different category. They flow, as it were, in closed pipes and often under heavy pressure. In many instances these streams are loaded to their utmost capacity with sand and gravel and contribute very largely to those fluvio-glacial deposits which are combined products of the glacier and the water derived from its melting. These play a great part in the deposits left behind by the retreating glaciers of the Pleistocene ice age and in Alaska they are conspicuous in present-day activity.

FIG. 143. — Part of terminal moraine, Dawes Glacier, Alaska. (Photograph by Buddington, U. S. G. S.)

Glacial Deposits, when made entirely by the ice, without coöperation by water, are entirely unstratified, for, as has been shown, a glacier has no sorting power, and débris of all sizes and weights is carried down together and deposited at the end, where the ice is completely melted, in a *terminal moraine*, which is a heterogeneous mass of coarse and fine, immense boulders and fine sand, pebbles and dust. All the material carried upon, within, or underneath the ice is dropped when the ice disappears. Most glaciers that terminate on land and do not enter the sea have ends, variously called "toes" or "snouts," which are rounded or bluntly pointed,

and the terminal moraine embraces the end quite closely and is therefore a curved ridge, with concavity upstream. The moraine may be breached in the middle by the outflowing stream, which has carried away the débris as fast as it was laid down.

Terminal moraines offer a great variety of form, determined by the condition of the glacier, whether stationary, advancing, or retreating. If stationary, the terminal moraine is built higher and higher and covers the toe of the ice; if advancing, most of the older moraine is pushed along and added to at each halt. If the

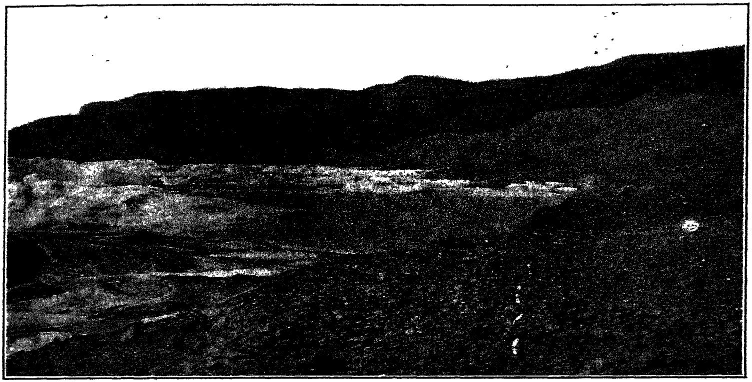

FIG. 144. — Terminal Moraine, Maier Glacier, Patagonian Andes. (Photograph by J. B. Hatcher)

glacier is retreating steadily, the moraine is a flat sheet, partly made up of the uncovered ground moraine. If, on the other hand, the glacier retreats with interruptions of a stationary condition, a succession of curved moraines, one behind the other, is left to mark the stages of retreat. Sometimes deep, funnel-shaped depressions, which may or may not be filled with water, are found in the area abandoned by the glacier, which are the marks of a *kettle moraine*. The kettle holes are interpreted as large blocks of débris-covered ice, which have become detached from the glacier in its retreat, and have caused the kettles by melting. On a small scale, this process may be observed in some of the retreating Alaska glaciers today.

FIG. 145. — Glacial drift, Bangor, Penn. (U. S. G. S.)

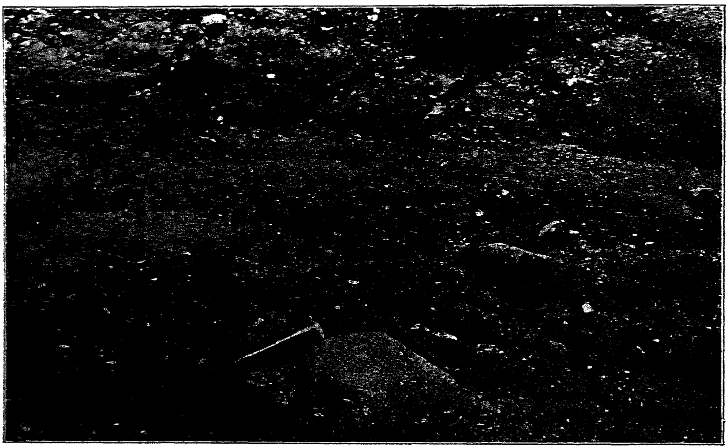

FIG. 146. — Glacial drift in Permian of South Africa. (Photograph by Rogers)

Ice Caps (or *Ice Fields*). Under existing conditions, this type of glacier is confined to high latitudes in both northern and southern hemispheres. Norway, Iceland, Spitsbergen, and the archipelago of Arctic North America are the northern examples. The ice cap is a flat dome, above which no rock rises, except sometimes at the margins; it covers completely the platform on which it lies, which is a small island, or a plateau, as in southern Norway. From the ice cap glaciers may descend as separate ice streams, again as in Norway and also in Iceland, but not in the Arctic archipelagos.

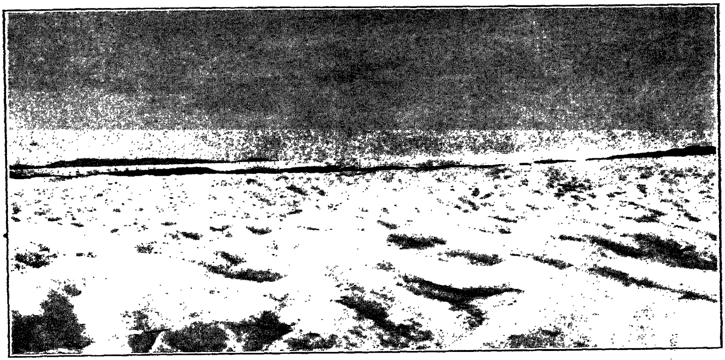

FIG. 147. — Looking northeast across inland ice of southwest Greenland. (Photograph by Prof. W. H. Hobbs)

As ice caps are intermediate between mountain glaciers and the inland ice, it is not necessary to give an account of their activities here.

Inland Ice (or *Continental Glaciers*), at present exemplified only by the vast ice sheets of Greenland and the Antarctic Continent, is looked to for an explanation of the many problems which the action of former continental glaciers offers to our attention. But several important differences in the conditions of climate and latitude give a reason for caution in drawing inferences.

The inland ice resembles the ice cap, has the shape of a much-flattened dome, highest in the mid-interior of the land mass and descending to the coasts. Except in the marginal zone, where it

is much thinned, no rock masses rise above the surface of the ice. In Greenland, Wegener's Expedition made sonic soundings through the ice to the bed-rock for a distance of 248 miles in from the coast to a point where the ice was 8,850 feet deep, and found that the bed-rock made a shallow dish, with curvature in the opposite sense of that of the ice surface. The dome rises to a height of 10,000 feet, more or less, above the sea-level, where there is no

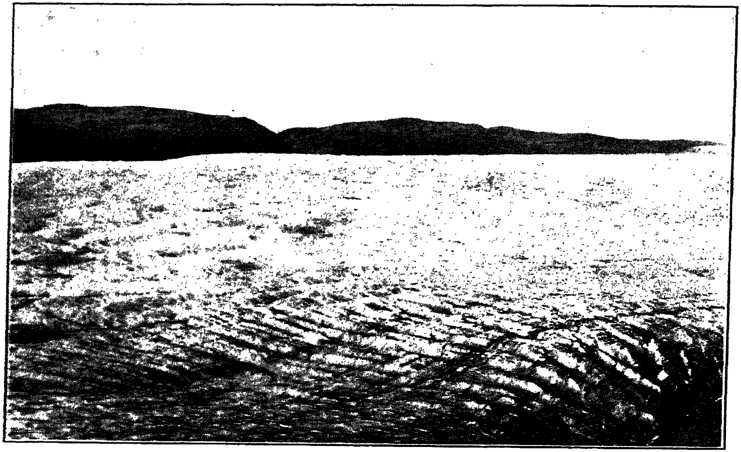

FIG. 148. — Otto Nordenskjöld Glacier, an outlet from inland ice of Greenland (Photograph by Prof. L. M. Gould)

melting in summer, except enough to form a thin crust over the snow. There is no loss by melting, and so low is the temperature that the relative moisture is always high, and therefore there is but little loss by evaporation. This explains the fact that the arid climate of Greenland, with a snowfall equivalent to only 10 inches of rain, supports this vast accumulation of snow and ice and supplies the annual waste of the marginal zone, where there is extensive melting in summer and also the formation of icebergs from the glaciers that enter the sea.

Nothing is known of the internal motions of the ice or snow of

the high lands. There is much reason to believe that a great part of the inland mass is stagnant and that the marginal zones of true ice, when there is extensive summer melting, is supplied by the wind, which is incessantly blowing clouds of snow before it, and partly by a slow creep from the higher levels. From the marginal zones, great glaciers descend through the mountain passes, many of them entering Baffin Bay. These ice streams move much faster than the glaciers of the Alps, but in the marginal zone of the inland ice the movement is very slow. Erosion is effected in the broad belt near the coast where the ice is demonstrably in

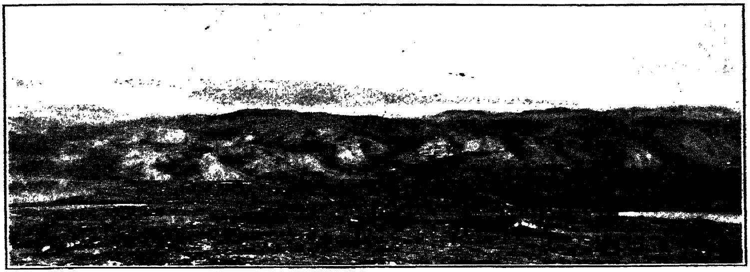

FIG. 149. — Nunataks near margin of inland ice, southwest Greenland. (Photograph by Libbey)

motion, and judging from the rocks recently uncovered by retreat of the ice, the polishing and striating of the bed-rock are the same as in the work of the mountain glaciers. Transportation by the inland ice is quite different from that performed by the mountain glaciers, for as no cliffs rise above the ice, there are, over far the greater part of the surface, no visible moraines. Nearer the coast, where the ice is much reduced in thickness, mountain peaks make their appearance; they are the *nunatak* of the Eskimo, which has been defined as "an island or rock in a sea of ice." Below each nunatak is a train of boulders, split off by frost action, but the sum total of surface moraine is small.

A considerable amount of englacial drift is shown in bands on the ice front, derived from wind-carried dust. Ground moraine is more extensively formed by material plucked from the bed and pushed up along the shearing planes. An obstruction, in the shape

Fig. 150. — Outwash plain from Nordenskjöld Glacier, southwest Greenland. (Photograph by Prof. L. M. Gould)

of a hard ledge projecting above the bed-rock, is an especially prolific source of débris. Such of the Greenland glaciers as do not enter the sea have no high, ridge-like terminal moraines, as do the mountain glaciers of Alaska or Switzerland, but a flat "outwash plain" of gravel and boulders. Fine material, sand and dust, is carried away by the wind and deposited in sheltered places.

Drumlins are hills of glacial drift, only partially or not at all stratified. Like *esker*, the word is of Irish origin. A drumlin is a hill of oval ground plan, the long axis of which is parallel to the direction of the ice movement. They usually occur in groups,

FIG. 151. — Drumlin, Jefferson Co., Wis. (U. S. G. S.)

often in great numbers, with long axes parallel to one another. The islands in Boston harbor are drumlins, most of which are bisected by wave action. In western New York are 6,000 of them and in Wisconsin 5,000. In height they are 100 to 200 feet and are from half a mile to a mile long. These strange hills all lie within the terminal moraine and are due, chiefly or entirely, to the ice, but no satisfactory explanation of them has been found, for nothing of the sort has been found in process of construction today, or in association with any of the existing ice sheets. Nor can their manner of occurrence be explained — immense numbers in certain localities and vast areas of glacial drift without a trace of them.

Kames are ridges of gravel and sand deposited by streams along the edge of the ice. Often such streams, as may be seen in

the Greenland summer, flow in channels of which one side is formed by a glacier. The difference between kames and eskers is that the latter were deposited by streams flowing upon, within, or underneath the ice, while kames were deposited on the border of the ice.

Erratic and Perched Blocks. The existing bodies of inland ice give us little information concerning a process which was endlessly

FIG. 152. — Erratic boulder, near Portland, Conn.

repeated in North America and Europe by the continental glaciers of the Pleistocene, and that is the transportation and deposition of immense masses of rock which were dropped when the ice melted, some of them on the terminal moraine, others all over the ice-covered area, as the glacier retreated. The scattered blocks and boulders, for many of them have been rounded by weathering, are called *erratics.* These immense rocks have traveled various

distances, from a few yards to hundreds of miles. The largest one known in the United States is a mass of granite at Madison, New Hampshire, and measures 90 × 40 × 30 feet, and must weigh over 65,000 tons. Another extremely large one is at Portland, Connecticut, and granite blocks, only a little smaller, and

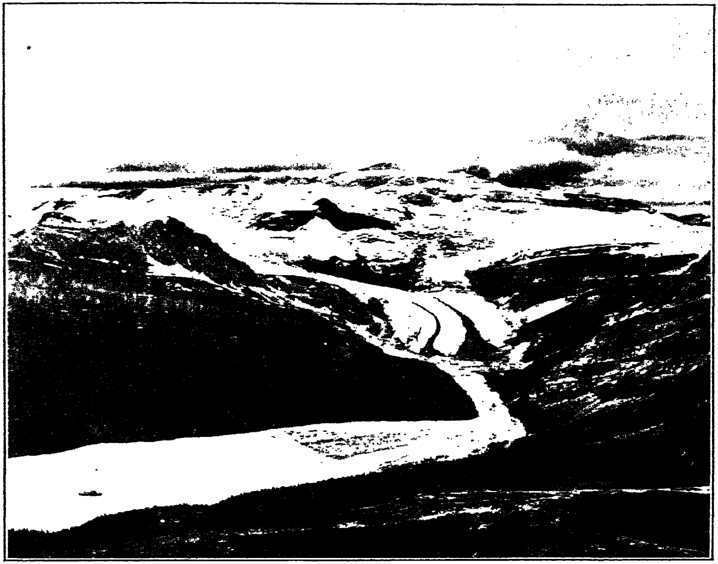

FIG. 153. — Alluvial fan, Lake Hector, Canadian Rockies. (Geol. Surv., Canada)

innumerable ones grading down to cobble stones in size, are scattered over New England and Long Island.

Huge as these are, they are insignificant in comparison with the gigantic masses of sedimentary rocks that the ice sheet transported for several miles in England; some of these are hundreds of yards in length and it is difficult to understand how the glacier could have picked them up.

Sometimes, though rarely, it happens that the melting ice slowly lowers a boulder and leaves it stranded on a rocky ledge, so balanced on a point that it may be moved back and forth with the hand. It is then called a "rocking" or "logging stone." Not all rocking stones are of glacial origin, though most of them are; sometimes a block is so undercut by weathering as to be balanced and movable. Figure 74 shows Cradle Rock, described by an eighteenth century European traveler as one of the greatest wonders of the world. The confused mass of blocks on which it

FIG. 154. — An esker, near Tweed, Ontario. (Geol. Surv., Canada)

lies looks like a glacial moraine, but is not; the blocks have weathered out of the Rocky Hill intrusive sheet, on which they still lie, and have not traveled at all.

Fluvio-Glacial Deposits are those made by the action of water derived from the melting of the ice in combination with, or in succession to, the action of the ice. Water pouring out from under the ice on a flat makes an *outwash plain*, or *overwash*, which it covers with sand, as do some glacier waters in Iceland and Alaska. The streams that flow beneath and from the foot of the glacier are loaded to capacity with débris and usually build up their beds by rapid deposition of the coarser sediment. This material in a valley forms a *valley train* and, being an aqueous deposit, is stratified. This may be distinguished from ordinary river deposits by their upward extension into moraines and by the glacial origin of the material. *Eskers* are long, winding ridges of gravel, which

often ramify so as to betray their origin as drainage systems; they were formed by subglacial or englacial streams which choked up their channels with gravel. The word *esker* is of Irish origin and has been used in so many different senses that it would be well to adopt the Swedish term *Åsar* as the Germans have done. Figure 154 shows a typical esker left behind by the retreat of the ice. Very similar ridges are frequent in England.

The Malaspina Glacier is more favorable to the study of fluvioglacial deposits than is the great inland ice of Greenland. The

Fig. 155. — Pleistocene varved clays, Milk Brook, Hanover, N. H. (Photograph by R. W. Sayles)

Malaspina has an area of 1,500 square miles and the Bering not much less. The outer portions of the glacier are stagnant and so covered with drift that no ice is visible. About the margins of the ice small lakes are formed, the waters being held in place by the glacier, but these lakes are subject to great fluctuation. In such lakes, fine clays are laid down in the plainly separated annual layers called *varves*. In very many regions, varved clays are found in association with the Pleistocene ice age and in both northern hemispheres. In the supposedly Permian glacial formation of Squantum, on the coast near Boston, varves are particularly well shown.

The streams flowing over the outwash plain, their waters derived from melting ice, are said to be *braided*, from the way in which they divide and subdivide and connect with one another by anastomosing branches. Some of this braiding is to be seen in Fig. 150; the large stones in the foreground have been carried down by ice floes.

Antarctica is in many ways entirely different from Greenland, especially in the fact that there the air temperature never rises to freezing point. Much remains to be done in the way of exploring and mapping this inaccessible land, despite the extraordinary

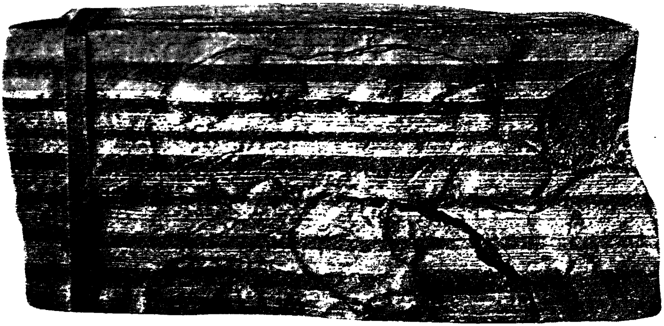

FIG. 156. — Varved slate associated with Squantum tillite. (R. W. Sayles)

heroism of the explorers. The especial peculiarity of the continent, the great ice barrier, will be mentioned in connection with sea ice. In view of the immensity of the ice fields, it is surprising to see how few glaciers extend to the sea.

Ground Ice (also called *anchor ice*) forms at the bottom of ponds and streams and freezes around stones and boulders, large and small; when the ice is broken up by thaws, masses of it drift away, carrying their load of débris, from sand and pebbles to large boulders, for long distances before melting causes the burdens to drop. In this way, rock masses, far too heavy to be carried by water, are readily transported by floating ice. The shores of the St. Lawrence River are fringed with large boulders thus brought down by ice. Sir Charles Lyell was much struck by this display of ice action.

Lake Ice produces some remarkable effects in northern latitudes, not too far north for an occasional break up and refreezing. When the lake is covered with ice fragments and freezing weather returns, the water between the ice cakes is frozen and expands powerfully, exerting heavy pressure against the shore. If the beach is boulder-covered, as is so apt to be the case in northern lakes lying within the glaciated area, the pressure of the ice pushes the boulders up into a ring wall, which has an artificial look.

Coast Ice. In far northern regions which have very severe winters, the shallow water along the coast freezes into a broad shelf of ice, called the *ice-foot.* The bottom is studded with sand, and pebbles and boulders, if there are any on the beach, and landslips cover the top with débris in the spring thaw. When the ice-foot is broken up, part of it drifts away, carrying its load of pebbles and rock fragments for long distances, perhaps out to the deep sea. Parts remain on the beach and are worked backward and forward by the waves and tides, striating the rocks of the coast, scratching and polishing the pebbles frozen in the ice. Sometimes an excellent imitation of glacial action is thus produced, but the small area and the position on the beach expose the deception.

For hundreds of miles, the coast of Antarctica is fringed with the ice cliff called the Ross Barrier, or the Great Barrier, or, more descriptively, as *shelf ice,* which varies in height above the sea from less than 50 to nearly 300 feet ; the shelf, which has a remarkably level top, is afloat on the sea and is in steady motion at the rate of about 1,500 feet a year. Where glaciers descend from the interior, they send out floating tongues which contribute to the barrier, but, for the most part, the portion above the water level is composed of snow. In the northern hemisphere there is nothing at all resembling the Ross Barrier, though there may have been such a shelf on the New England coast in the Pleistocene ice age and another on the coast of Greenland.

Icebergs. The icebergs of the Arctic and Antarctic seas are entirely different in shape, appearance, and mode of origin. Aside from the small icebergs of Alaska, which are of no importance, all the icebergs of the northern hemisphere are in Atlantic waters and are derived from Baffin Bay, where many great glaciers descend from the inland ice and enter the sea. Such glaciers plow along the bottom until the buoyancy of the water forces the foot of the

glacier to rise and float, breaking from the parent mass and drifting away as an iceberg. Currents carry the bergs down the bay and into the Atlantic, where some have been met with as far south as the Azores. They melt irregularly and take on fantastic forms; immense as many of them are, only about one-eighth of their bulk appears above the water. They are lighter, and float higher than ice entirely free from air would do. The geological importance of icebergs is entirely in a small amount of transportation and deposition. As they are fragments of glaciers, each berg carries away whatever débris that particular fragment held frozen within it. Thus Greenland rocks are scattered thinly over the bed of the North Atlantic and in its greatest depths.

The Antarctic icebergs are remarkable for their tabular, rectangular form; the portion which appears above water is relatively long and low, yet they float high, because they are mostly composed of snow, being detached portions of the floating barrier that surrounds the continent. They carry very little débris.

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CHAPTER XV

LAKES, PLANTS, AND ANIMALS

The term *lake* is a very comprehensive one and includes all continental bodies of water not in tidal connection with the sea, in which the water is relatively stationary, not running, as in a stream. If a lake has an outlet, it is situated at the lowest point of the retaining barrier, and the water flows, though with extreme slowness, toward that point. The Lake of Geneva is 45 miles long and the rate of movement of its waters has been determined; a given drop of water requires eleven years to pass from one end of the lake to the other. This is practical stagnation and makes plain why lakes act as settling basins; throwing down all particles of the sediment which is carried in by tributary streams. Normally, the water of lakes and their outlets are exceptionally clear. From the geological point of view lakes are ephemeral and must sooner or later disappear, either by the filling of their basins with sediment, or by cutting through of the retaining barriers and so draining the basins. Lakes are formed in a number of different ways; most of them occupy depressions, the bottoms of which are below the general drainage level of the region and often below the level of the sea. Other lakes are impounded by barriers and these are usually above the drainage level.

The dams may be of the most varied sort, glacial moraines, lava streams, the débris of great landslips or rock slides which block up a valley, or the delta of a tributary, which brings in more sediment than the trunk stream can carry away. Great lakes that are relatively long-lived are contained in basins, often of great depth, which were formed by diastrophic movements of the earth's crust. The other varieties are more evanescent and usually of rather small size.

Lake Erosion. Small lakes accomplish almost nothing in the way of rock destruction, being places of accumulation. In great lakes, such as those which are drained by the St. Lawrence, very heavy surf is generated in storms, and this attacks the shores in

much the same way as the sea does, but less effectively, for, on account of the absence of a tide, the work of the waves is confined within narrower limits and the lake cannot spread indefinitely over the land as the ocean can. Nevertheless, the cut bluffs and cliffs, dependent upon the height and boldness of the shores, reveal the destructive work of lakes. The form of beach lines, so long as they persist, record the different levels of the lake. Raised beaches on the seashore are nearly always due to an upheaval of the coast, but the deserted shore lines of a lake are the result of changes in the water level. A diastrophic elevation, or depression, would raise or lower the lake bottom and its shores together, causing no relative change. The two principal classes of lakes, fresh and salt, while doing similar erosive work, have characteristic differences in deposition, though not always, for the chemical deposition in salt lakes requires a degree of concentration in the solutions which is attained comparatively seldom.

A. Lacustrine Deposits

In fresh-water lakes, deposition is mechanical and, in very subordinate degree, organic also. In salt lakes it is mechanical, and if the necessary concentration is attained, chemical precipitation becomes more important.

I. Fresh-Water Lakes

1. *Mechanical Deposits* are principally of the sediment which is carried in by streams, with the addition of the material provided by the attack of the lake on its own shores. Almost without exception, streams entering a lake form deltas, which spread out in fan-like shape from the mouths of the streams. If the tributaries are sufficiently numerous, they will fringe the lake shore with delta deposits. That, however, occurs only in small lakes. Part of the river-borne material is distributed by waves and currents, but the coarser particles are thrown down to form the fore-set beds, the inclination of which depends upon the depth of the lake at the point of entrance and upon the coarseness of the sediment. Small lakes are filled up by the coalescence of the deltas or the outgrowth of a single one, forming, first, swamps, then smooth, grassy meadows, through which flow the streams keeping open their own channels.

Away from the deltas, the action of waves and currents form beaches of gravel and sand, the latter extending for some distance out into shallow water. Figure 157 shows a beach on Lake Ontario, covered with large, flat pebbles of sandstone, derived from the neighboring shores. In size, the pebbles are obviously graded from small ones near the water's edge to very large ones on the upper part of the beach where only the surf of heavy gales can break.

In large lakes, the surf, which is very violent in storms, cuts back the bluff or cliff and forms a terrace on the shore, which is

FIG. 157. — Gravel beach, Lake Ontario. (U. S. G. S.)

extended outward by deposition of the débris thus obtained; the terrace is then said to be "cut and built." The finer materials are carried out to deeper water and deposited in layers over the whole lake bottom. The coarse and fine sediments grade into each other, dovetail and overlap, because in heavy storms, or when entering streams are in flood, coarser débris is carried out and deposited on the finer. There is, however, a limit to the distance to which gravel and sand are ever carried, and in large, deep lakes, much the greater part of the bottom is covered with the finest clay and marl. The action of currents forms special lines of accumulation for the coarse substances and builds up shoals, spits, embankments, and the like.

Fig. 158. — "Parallel roads" of Glen Roy, Inverness, Scotland. Three successive lake terraces made by glacier-dammed lakes in the Pleistocene epoch.

The five Great Lakes, also called Laurentian, occupy a relatively small drainage basin and receive no large tributaries, so that the large volume of overflow, which is carried by the St. Lawrence, must be chiefly supplied by springs and underground water courses. There is comparatively little coarse material, and this is supplied mostly by the work of the lakes themselves, and the deposits now forming are principally blue muds and clays, partly made of kaolin and partly of the débris of other minerals in an extremely fine state of subdivision, but not chemically decomposed. In Lake Superior the clay is pinkish rather than blue.

An abandoned lake basin is marked out by the manner in which its deposits are arranged, but more or less of these loose materials is soon swept away by the eroding agents. In an arid climate the original form and arrangement of the deposits may persist for many thousands of years, and even in the pluvial climate of the Middle West the complex history of the Great Lakes is still surprisingly legible. Excellent examples of abandoned lakes are to be seen in the Great Basin, their features so well preserved that it almost seems that the waters had withdrawn but a few years ago. To the large body of water, of which the existing Great Salt Lake is the shrunken remnant, the name of Lake Bonneville has been given. The drying up of this lake, which once was fresh and had an outlet northward to the Snake River, a branch of the Columbia, is an event so recent geologically that its size, shape, depth, its islands, bars, and beaches, in short its history, can be made out with the greatest clearness and detail, as was admirably done by the late Mr. G. K. Gilbert, of the U. S. Geological Survey.

At its time of greatest extension, Lake Bonneville had an area of 19,750 square miles, nearly two-thirds the size of Lake Superior, and had the very moderate maximum depth of 1,050 feet. Salt Lake, though variable, had in 1869 an area of 2,170 square miles and an extreme depth of 46 feet. The different levels of the lake, at various stages of its history, are perfectly registered in the beach terraces, which are so conspicuous on the flanks of the Wasatch Mountains that they have attracted the attention and wonder of nearly all travelers. The embankments, bars, gravel and sand spits mark the shallows, and most of the basin is an exceedingly flat plain, the Salt Lake Desert, which is filled to a great, but undetermined depth with beds of very fine clay and marl. The

mountains, which rose as rocky islands above the water, now rise above the lake floor and have a half-buried appearance. In more ancient lakes the shore features have been removed by erosion and only the deposits of the deeper part of the basin have been preserved. Such remnants of geologically old lakes cannot always be assuredly distinguished from the flood plains of rivers.

2. *Chemical Deposits* are not common, nor of great importance in fresh-water lakes, especially the larger ones. In some small lakes calcium carbonate is precipitated, and more abundant is the iron-ore limonite ($2\,Fe_2O_3$, $3\,H_2O$). The iron is brought in, as ferrous carbonate ($FeCO_3$) dissolved in water, by tributary streams, and partly by the action of the iron bacteria, partly by contact with the air, the carbonate is converted into oxide. In Sweden, ores of this kind are dredged from the lakes and used as a source of the metal.

The "parallel roads" in Glen Roy and other Scottish glens were long famous as unexplained structures, until L. Agassiz suggested that the key of the mystery lay in temporary lakes made by the damming of the glens by ice-streams which flowed past their open ends. (See Jamieson.)

3. *Organic Deposits* are seldom important in large lakes, but often decidedly so in small ones. Masses of water plants may spread from the shores and bottom, choking the lake and converting it into a bog, in which peat, or partially decomposed, carbonized vegetable matter, is accumulated. *Diatoms*, microscopic plants which secrete beautiful tests, or shells, of silica, multiply with great rapidity and gather on lake bottoms as a fine white powder, variously called Tripoli, or polishing powder, or infusorial earth. Diatoms live also in the sea and in brackish water, but it is only in lakes that they form accessible deposits. Calcareous accumulations are made of the shells of pond snails and other fresh-water molluscs, often of considerable thickness and extent. When loose and incoherent, such accumulations are called *shell marl*, and the lower portion of it is so disintegrated by the water as to be without any obvious organic structure. Shell marls are often found under peat bogs and indicate that the bog was originally a lake, until filled up by vegetable growth. Bones of extinct animals are often found in the marl. When cemented into a firm rock, the marl forms a fresh-water limestone.

II. Salt and Saline Lakes

Salt lakes are those in which common salt ($NaCl$) is the principal ingredient of the dissolved materials. A *saline* lake is a more comprehensive term, which includes not only ordinary salt water, but likewise all other salts in solution, such as soda, borax, potash, alum, etc. Saline lakes of all kinds are confined to arid regions, where rainfall is light and evaporation great; in the Great Basin, for instance, the annual rainfall is less than 20 inches, and the evaporation over 60. Such lakes may be formed in either one of two ways: (1) The separation of bodies of salt water from the sea. This is exemplified by the Salton Sink in the desert of southeastern California, which is considerably below sea-level and in 1900 was partly converted into a lake by the eruption of the Colorado River. Originally, the Sink was the head of the Gulf of California, as is indicated by the old beaches, shell-banks, etc., which still remain. The Colorado River, which entered the Gulf from the east, some distance below the north shore, built its delta across the Gulf, converting the upper end into a salt lake, which subsequently disappeared by evaporation. Beds of salt remain to demonstrate the lacustrine stage.

(2) The second method of saline lake formation is by the long-continued concentration of river water in basins that have no outlet and where surplus water is removed by evaporation. The size of the lake is determined by the balance between influx and evaporation, the level rising at the season of high water in the tributaries and falling when the tributaries are lowest and evaporation most rapid. Beside these seasonal variations of the lake level, there are periodic alternations of wet and dry years, and irregular times of greater or less precipitation. These factors cause fluctuations in the level and consequent size of salt lakes, which do not occur in lakes that have an outlet.

The history of Lake Bonneville gives an excellent illustration of the change from fresh to saline conditions. As long as the water level remained above the outlet, the lake was fresh, but when advancing aridity of climate diminished precipitation and increased evaporation, the lake began to shrink until the surface fell below the outlet and the balance of influx and evaporation was established. The various substances dissolved in the water of the tributary streams remained in the lake, and the proportion of

dissolved solids steadily rose until the lake became brackish and then salt. Great Salt Lake, the "boiled down" remnant of Bonneville, is intensely salt and bitter and the water is so dense that a swimmer floats in it almost like a cork.

As has been seen (p. 266), river water always contains many solids in solution, and of these one of the most abundant and widespread is common salt; and the continual influx and evaporation of river water cause the lake to become more and more saline, till it reaches saturation. The salt is mostly, though not altogether, derived from rivers; desert soils and surfaces contain it, and on the Pampas of Argentina, which cannot properly be called a desert, salt crusts frequently form. Wind and rain thus carry additional salt into the lake.

1. The *mechanical deposits* laid down in salt lakes do not differ in any essential way from those made in fresh water. The finer, flocculent clays settle more rapidly in brine, and strongly saline lakes are extraordinarily clear. Organic deposits in salt lakes are practically absent, for very few animals or plants can exist in strong brine, and those that do so are not of the sorts that form accumulations of peat, or calcareous, or siliceous material. For the same reason, deposits of any kind made in salt lakes are almost barren of fossils, except of such land organisms as may be brought in by flooded streams.

2. *Chemical deposits* are much the most important of the accumulations made in salt lakes and they differ in various lakes according to the composition of the rocks in the drainage basins, but while some of these materials are rare, others are exceedingly common and widely diffused. The deposition of the salts is an extremely complex matter, the more so the larger number of ingredients present in solution. In general, the precipitation follows the inverse order of solubility, the least soluble being thrown down first and the most soluble last. Little chemical reaction would seem to take place in these lakes; the salts are nearly all those laid down by the evaporation of saturated solutions and are the same as those brought into the lake, in very dilute form, by springs and streams. If the precipitation of salts is slow and occasional, the chemically and mechanically made deposits are mingled together; but if the precipitation be rapid, then thick and nearly pure masses of the salts are thrown down in their inverse order of solubility, as the concentration proceeds.

The first substances to be deposited from solution are calcium carbonate ($CaCO_3$) and ferric oxide (Fe_2O_3) and, in moderately saline lakes, this is about the limit of precipitation of dissolved materials. These same compounds, as has been noted, are also laid down in fresh-water lakes, their deposition being principally due to the loss of the solvent carbon dioxide (CO_2). The ancient Lake Lahontan, contemporary with Bonneville, occupied part of northwestern Nevada and, being without outlet, built up calcareous deposits on a grand scale; every cliff and island which its waters touched is sheathed in thick masses of calcareous tufa. Pyramid Lake, a remnant of Lahontan, has a remarkable island of such deposit, and in Mono Lake, California, the same material has assumed bizarre shapes.

As the concentration of the lake water proceeds, the next substance to be precipitated is gypsum, or calcium sulphate ($CaSO_4$, $2\,H_2O$), which is only sparingly soluble, yet much more so than calcium carbonate. Gypsum is precipitated from cold water, anhydrite ($CaSO_4$) from hot, and the two minerals may occur in succession, or association, as they do in the province of New Brunswick on a large scale. After the calcium sulphate has been eliminated, whether as gypsum, or anhydrite, the solution of salt must be much farther concentrated before deposition begins. Even such dense brines as those of Great Salt Lake and the Dead Sea are not depositing salt, though they are not far from the saturation point. After that point has been reached, salt begins to go down and continues to do so as long as concentration proceeds. At an advanced stage the salt is mingled with magnesium sulphate ($MgSO_4$) — should that be present in the water.

The "soluble chlorides," those of potassium, magnesium, and calcium (KCl, $MgCl_2$, $CaCl_2$), which will dissolve in the water they take from the air in an ordinary room, are always present in brine; in salt-making the solution of them forms the "mother liquor," which must be drained away from the salt crystals and the latter washed, to free them from all trace of these bitter compounds. They are not deposited except when the water is evaporated to dryness and then they form various compound salts with one another and with the chloride of sodium, the latter continuing till the very end of the process. On account of their potassium content, these compound salts are of very great economic value; they are principally mined at Stassfurt, in Prussia (hence often

called "the Stassfurt salts"), and, less extensively, in Alsace; they are known to occur in Spain and Morocco and have been found in Texas, though it has not yet been ascertained whether the Texas deposits are commercially practicable. In very dry climates, as in western Texas and central Asia, salt may lie on the surface in great masses. Lop Nor, in Turkestan, is a large salt body which marks the site of a dried-up lake.

The order of deposition in a salt lake, as outlined above, is subject to interruption. In seasons of high water the flooded tributaries dilute the lake water and cause chemical precipitation to cease and, at the same time, increase mechanical deposition of the burden which the swollen streams bring in. Thus clastic sediments, sand, mud, etc., are laid down upon beds of salt and gypsum, alternating with them, as evaporation or the influx of fresh water predominates. Changes of temperature may also produce different compounds. In cold weather, the Great Salt Lake washes up on its shores windrows of sodium sulphate (Na_2SO_4), Glauber's salt, which is formed at low temperatures by the double decomposition of sodium chloride and magnesium sulphate.

Besides the chemical deposits in saline lakes already mentioned, there are others which occur on a much smaller scale. On the western side of the Great Basin, in Nevada, California, and Oregon, are several lakes, whose waters hold in solution quantities of sodium carbonate ($NaCO_3$), and in some the solution is so concentrated as to cause precipitation. In other lakes borax, or sodium tetraborate ($Na_2B_4O_7$, 10 H_2O), is contained and is deposited in very dry climates, as in Death Valley and the bitter lakes of central Asia.

Much the most abundant of the chemical deposits made in salt lakes are gypsum and rock salt and their frequent association is thus explained. Concentration may not have proceeded far enough to precipitate salt, in which case gypsum alone would have been deposited. Vast bodies of rock salt are preserved, lying below the level of circulating water, though brine springs show that some salt bodies are in process of removal by solution. One of the most enormous of the known accumulations of salt is that which underlies the north German plain. The famous artesian well at Sperenberg passes through 3,907 feet of salt. In several parts of the United States, notably in New York and Kansas, large bodies of salt occur, though on no such scale as those of Europe.

Salt masses of such immense extent and thickness, with little or no mechanical sediment interstratified within them, are not easily to be explained by the usual operations of a salt lake as above described. The explanation has been sought in various other bodies of salt water, such as cut-off parts of the sea, like the Salton Sink, or almost separated gulfs, such as Kara-boghaz, connected with the Caspian Sea by a very narrow neck. All that can be confidently asserted is that the salt has been precipitated from solution in water through evaporation in arid regions. A salt-body is proof of aridity of climate at the time and place of the deposition.

B. Organic Agencies

By the term *organic agencies* is meant the work done by animals and plants while living, and accumulations of their remains after death; the latter are much the more important.

1. *Protective Effects.* In connection with weathering, something was said (p. 218) as to the protection of soil and rock by organisms, almost entirely plants, since, on land, animals are not sufficiently abundant to produce any such effect. A thick covering of vegetation, especially the elastic, matted roots of grass, protects the soil against rain wash.

Forests are very important protectors of the soil, especially on steep slopes, and when the forests are cut off, the soil is rapidly washed away with the disastrous results described in the chapter on rain. Sand and light, loose soil are at the mercy of the wind unless protected by plants. Long-rooted, rapidly growing grasses are the best means of halting the movement of shifting sand dunes, and trees are very efficient as wind breaks. Sands from the Bay of Biscay coast, driving inland before the prevailing westerly winds, threatened to overwhelm great areas of farm and pasture land in the southwest of France. The French government succeeded in arresting the movement by planting coniferous trees, which broke the force of the wind and held the sand in place. Even the shores of rivers and the sea may be protected by vegetation; dense masses of seaweed growing on the rocks form an elastic buffer against the waves, and on low-lying tropical coasts the mangrove trees, with their interlacing aërial roots, so break the force of the surf that it cannot wash away even fine mud.

The only protection given by animals that should be mentioned

is that of coral reefs, which, directly fringing the coast, or running parallel with it, act as breakwaters and effectively shield the shore line against the waves.

FIG. 159. — Soil destruction owing to removal of forest, Mitchell Co., N. C. (Courtesy of the U. S. Bureau of Forestry)

2. *Destructive Effects* of organic agents are far inferior in efficiency to the agencies described in the foregoing chapters — or that remain to be considered, like the sea. In the unimaginable lapse of geological time, effects that seem trivial now are so multiplied as to become important. The work accomplished, directly or indirectly, by bacteria is only beginning to be understood and is

certain to increase greatly in importance with the advance of knowledge. We know already that these microscopic plants are well-nigh ubiquitous, that they exist in countless multitudes in the soil, in fresh waters and in the sea and that they are the indispensable factors in the decomposition and putrefaction of organic matter and have direct effects, not yet demonstrated in the disintegration of rocks. It has been suggested, but not proved, that laterite, the peculiar red soil of the tropics, is a result of bacterial activity. No one can yet foresee what the limits of this activity in the soil and in the muds and oozes of the sea floor will eventually be found to be, but we may safely assume that the limits will be very wide.

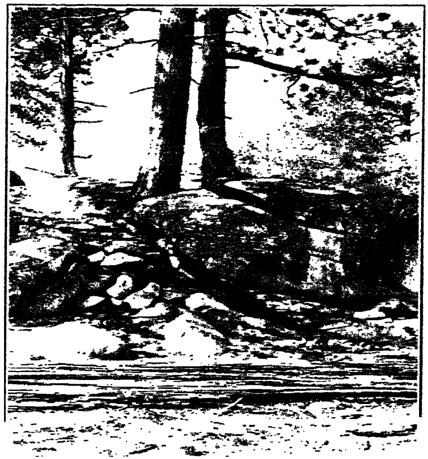

FIG. 160. — Splitting of granite by growing tree roots, Sierra Nevada, Cal. (Photograph by Gilbert, U. S. G. S.)

Growing plants enlarge the diameter of their roots with a force of expansion comparable to that of freezing water. Seeds germinating in the crevices of a rock, or the roots of trees which invade such crevices from above, wedge the joint blocks apart and large areas of rock are thus effectively broken up. In Fig. 160 the large root of a pine tree is seen to be wedging apart a granite boulder by the force of growth. In Fig. 161 may be seen the manner in which the roots of a tree break up a limestone. Living roots also secrete an acid which dissolves some of the constituents of rocks, thus adding chemical activity to the mechanical effects.

More effective than the destructive work of living plants is that done by the results of their decay and is therefore indirectly the work of bacteria. Vegetable decomposition in the soil, where the

air supply is limited, generates a long list of organic acids, including carbon dioxide and the humic acids. Some of these are deoxidizers and will convert insoluble hæmatite (Fe_2O_3) or the hydrated form limonite into the soluble ferrous carbonate (Fe_2CO_3). In this manner a red sandstone, which, when built into a wall above ground, will remain unaffected by the weather for centuries, may crumble to sand in a few years underground. Other rocks are affected in similar fashion, though the chemical details are different. A loose block of stone, dug out of the soil, may seem sound and hard, but, when broken open, will display a larger or smaller center of unchanged rock, surrounded by a zone of entirely different color, the incipient stage of disintegration.

FIG. 161. — Fallen tree having roots filled with blocks of limestone, Black Hills, S. D. (Photograph by Darton, U. S. G. S.)

The destructive work done by animals is relatively small; many marine creatures bore tunnels in rocks, even the hardest, and cause them to crumble, and a great variety of land animals continually burrow in the soil, allowing a freer entrance to water and air. In the tropics, the ground is fairly alive with burrowers in multitudes, ants and termites (the so-called white ants) are extremely active in tunneling the soil.

In semi-arid regions, many kinds of burrowing mammals, in incredible numbers, are constantly working over the soil to great depths, as do the "prairie dogs" of the Western plains. The occasional heavy rains thus penetrate to depths not otherwise reached.

In pluvial regions, which do not have too severe winters, the soil contains countless earthworms whose geological activity formed the subject of Mr. Darwin's last book. Earthworms are constantly swallowing the soil for the sake of the organic matter in it, and grinding it to excessive fineness in their muscular gizzards. The ground-up soil is brought to the surface at night, especially after a rain, and voided in the shape of the coiled "worm castings,"

which are so abundant in grassy places. Worms confined in a flower pot filled with white sand and supplied with fresh leaves in a few weeks covered the sand with a layer of vegetable loam. Worms are continually bringing soil from below and depositing it on the surface, while, by collapse of old burrows, the first surface gradually sinks. In England, as Mr. Darwin tells, the material annually deposited by worms on the surface of the ground varies from seven to eighteen tons per acre, according to the numbers of worms, which is equivalent to a deposit of one-tenth to one-sixth of an inch annually per acre. This explains the puzzling fact that stones lying on the surface of the ground gradually sink into it and seem to bury themselves of their own weight.

C. Plant Accumulations — Swamp Deposits

For the preservation of vegetable accumulations a certain amount of water is necessary to prevent complete oxidation and consequent disappearance of the plant remains. Organic decomposition is the work of bacteria, but the result is *as if* the oxidation were a matter of chemistry and, for the sake of simplicity, it may be so treated here. Vegetable matter is composed of carbon, hydrogen, oxygen, and nitrogen, with a certain proportion of mineral matter which remains after the rest has been burned and is called *ash*. When exposed to the air, dead plants are completely oxidized and form compounds which are nearly all liquid or gaseous and so are dissipated without leaving any residue. Gases are carbon dioxide, marsh gas (CH_4), and ammonia (NH_3), while water and the more complex humic acids are fluid. In old forests the accumulation of dead leaves, branches, even occasional fallen trunks, which has been going on for centuries, results only in a thin layer of vegetable mold. Under water, the oxygen needed for effecting decomposition is not that which is combined with hydrogen, but the free gas which is dissolved in water, and this is very limited in amount, insufficient for complete decomposition of the vegetable matter. Some carbon dioxide, water, and marsh gas are formed, but nearly all of the carbon, much of the hydrogen, and some nitrogen are retained. The further decomposition proceeds, the higher does the *proportion* of carbon rise and the darker does the color of the mass become.

Peat-bogs are extensively developed in northern countries: Canada, New England, Scandinavia, and North Germany; one-

tenth of the surface of Ireland is covered with peat-bogs. The northern bogs, which flourish in cool, damp climates, are made by the bog moss, *Sphagnum*, which is the reason why, in Scotland, a bog is called a moss. Bog moss will hold water like a sponge and develop a bog in any shallow depression, or even on a flat surface where the plant can get a foothold. The mosses form dense and tangled masses of vegetation, dead and decaying below, growing and flourishing on the surface. The depth of the peat may be as much as fifty feet and its fineness of grain and compactness increase with the depth; in part, this is due to the longer time which the lower part of the peat has been macerating in water and, in part, to the pressure of the overlying mass.

In warmer climates peat-bogs are not so common and a different kind of vegetation forms the material. Peat frequently forms in small lakes and ponds, aquatic plants growing out from the shores, until they fill up the basin and convert the pond into a bog, as previously described. (P. 342.)

The vast quantities of coal in the world, some of which is found in every continent, show the great importance which the accumulations of vegetable matter under conditions which lead to partial decomposition have had in the earth's history. Perhaps the Great Dismal Swamp of Virginia and North Carolina reproduces more closely than other existing bogs the conditions of the ancient swamps in which were accumulated the great masses of vegetable matter that now are coal. The swamp, which measures thirty miles in length by ten miles in width, is, in size, insignificant in comparison with the vast bogs of the Appalachian and mid-Western coal fields. It is a dense growth of vegetation upon a water-covered soil of pure peat of not more than fifteen feet in depth and with no admixture of sediment. In cross-section the peat is lenticular, thinning from the center to the edges and with a depression in the middle which contains the clear sherry-colored water of Lake Drummond. The swamp cypress tree (*Taxodium distichum*) grows abundantly in the bog and prevents by its shade the evaporation which would otherwise take place in summer. The shallow layer of water which covers the ground receives the leaves and twigs which the cypress annually sheds, occasionally larger branches and the trunks of dead trees, while the dense growth of mosses, ferns, and herbaceous plants that carpet the surface add their quota to the mass of decaying vegetation. At

the bottom of the bog is a layer of fire clay, impervious and tending to hold the water in place. Similar peat-bogs are found at the mouth of the Mississippi.

Fire Clay, as previously defined (p. 183), may have a large admixture of sand, but is very free from the alkalis and alkaline earths, such as lime or magnesia, and has very little iron. The bog

FIG. 162. — Great Dismal Swamp, Va. (U. S. G. S.)

water, though passing through the clay with extreme slowness, yet leaches out these substances. Fire clay is very frequently found beneath a coal bed and the association is thus not accidental.

Bog Iron Ore. Iron is one of the most widely diffused of substances, most rocks and soils containing some of its compounds. Most of these compounds are insoluble in water containing carbon dioxide, but ferrous carbonate ($FeCO_3$) is soluble in such water, first forming, no doubt, the bicarbonate, as is also the case with calcium carbonate. We have already seen that in the soil, at

no great depth below the surface, ferric oxide (Fe_2O_3), whether hydrated or not, is deoxidized and converted into the soluble carbonate in a manner that does not occur above ground and in the free air. How far this conversion is purely chemical, effected by the humic and other acids derived from plant decay, and how far it is due to the action of the bacteria which abound in the soil, it is not yet possible to say. Very probably both methods are effective.

Similarly, it is not possible to say how largely the concentration and deposition of the iron is bacterial and how far chemical, for it is quite certain that deposition is accomplished in both ways. Water which contains ferrous carbonate in solution is, when freshly drawn from a well or spring, perfectly clear and limpid. The taste of such water is decidedly suggestive of iron rust, and when it is allowed to stand in an open vessel, speedily throws down a rusty deposit, which is hydrated ferric oxide. Here the process is chemical: the oxygen of the air attacks the ferrous carbonate, causes it to release the carbon dioxide and combine with enough oxygen to re-form the ferric oxide. Chalybeate springs and streams stain their banks red by depositing the oxide.

On the other hand, there is a large group of bacteria, the "iron bacteria," which take up iron in solution, oxidize it, and excrete it. If chalybeate waters gather at the bottom of a bog and bacteria do not act upon them, siderite ($FeCO_3$) is deposited from solution out of contact with the oxygen of the air.

The great accumulations of calcareous material in the sea are considered in Chapter XVII in connection with marine deposits.

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CHAPTER XVI

THE SEA — DESTRUCTION

The erosive work of the sea is, indirectly, due to the wind, for the chief agents of marine destruction are the wind-made waves and currents, though the tide reënforces and extends the power of waves and itself generates important currents. Both in erosion and in deposition, depth of water is a very important factor in determining the nature of the work accomplished, and therefore an account of the form and character of the ocean basins is prerequisite to an understanding of the work done in them.

The nature of the bottom in the deep sea is now fairly well known for the North and South Atlantic, but the soundings so far made in the other oceans are very inadequate to a knowledge of their basins. One of the few good results of the World War was the development of "sonic sounding" by the United States Navy, by means of which a sound is generated in the water, is reflected from the bottom, and by determining the difference in time between the starting of the sound and the return of the echo, and knowing the speed of sound-waves in water, the depth of water is given. The German naval surveying ship, *Meteor*, has recently (1925–28) made a remarkable voyage of exploration in the South Atlantic, crossing the ocean 17 times from South America to Africa and return and taking a sonic sounding every 20 minutes while at sea. This gave a total of 33,000 double soundings, for two different methods were used simultaneously, and at short intervals these were checked and verified by taking a sounding in the old way, with heavy weights attached to a steel wire.

The results of the *Meteor's* cruise have, as yet, been published only in preliminary form, but they are sufficiently remarkable and revolutionary to have attracted wide attention, and it would be premature to extend the results gained in the South Atlantic to other ocean basins, which may be quite different in character. All of the oceans, of which geographers now admit but three as

distinct, overflow their basins, submerging more or less of the continental platform. This submerged part of the platform is called the *continental shelf* and varies greatly in width, from 10 to 150 miles. The edge of the shelf is commonly, but by no means always, marked by a depth of water of 100 fathoms, which is therefore taken as the boundary of shallow and deep water. In some places the edge of the shelf is in 50 fathoms, in others 200; there is no rule about it, but the 100-fathom line is more usual. From the shore to the margin of the continental shelf the descent of the bottom is very gradual; off the east coast of the United States it is only 6 feet to the mile, bringing the 100-fathom line 100 miles out from shore.

From the edge of the shelf the descent of the sea-bottom is steep, with grades differing much on different coasts. This *continental slope*, as it is called, has a grade of 13° or 14° off most of the west coast of Europe, but is much steeper in places.

A. Marine Erosion

1. *Wave Action.* The erosive or destructive work of the sea is principally confined to the coast, from a little below low-tide mark to considerably above high tide, for in violent storms on bold coasts the waves cause damage as much as 200 feet above sea-level. On flat, low-lying coasts they reach no such heights. The attack of the sea on the land causes the coast to recede at a rate which differs greatly according to the conditions. Low, sandy coasts may be advancing into the sea, bold coasts are cut back at a rate depending upon the violence of the surf and the hardness of the rocks. A coast which, like that of the eastern and southern shores of England, is steep and bold and has cliffs of rather soft rocks will retreat most rapidly, while cliffs of granite and gneiss, like that of Maine, are but slowly acted on. The movements of water under the impulsive force of wind and tide are extremely complex, but for geological purposes these may be much simplified.

The wind-made waves of the ocean act continually upon all coasts, but with very different force at different times and places. According to the Scottish Lighthouse Board, the average wave-pressure, calm and stormy days included, on the Atlantic coast of Scotland is, for five summer months, 611 pounds per square

foot and for six winter months 2,086 pounds. The maximum pressure recorded was 6,083 pounds and on the east coast pressures exceeding 6,000 pounds were measured. The vast power of these storm-waves produces results which seem all but incredible; in 1836, in a heavy gale, the waves washed stones of 3½ tons weight from the breakwater at Cherbourg in France, over a wall 20 feet high. Similarly, as shown in Fig. 164, the great stones for the

FIG. 163. — Storm-wave striking sea-wall at Rio de Janeiro. (Gift of Prof. B. Willis)

breakwater at Holyhead were washed back and forth over that structure, with much damage to it, by a great storm.

The list of such astonishing performances in various parts of the world might be indefinitely prolonged. For lack of space, it must suffice to mention the most remarkable illustration of the enormous power of storm waves that has yet been recorded. The account, taken from T. Stevenson's book, *The Design and Construction of Harbours*, is thus given by Professor D. W. Johnson. At Wick, in almost the extreme northeastern corner of Scotland, there was at the seaward end of the breakwater a monolith of concrete,

anchored to large stones by iron rods of $3\frac{1}{2}$-inch diameter. "The entire mass, weighing 1,350 tons, was torn from its place by the waves [in a gale of December, 1872] and dropped inside the pier, where it was found unbroken after the storm had subsided. A much larger mass of concrete was substituted for the one removed, the new block having a volume of 1,500 cubic yards and weighing 2,600 tons. In 1877 this enormous mass was similarly carried

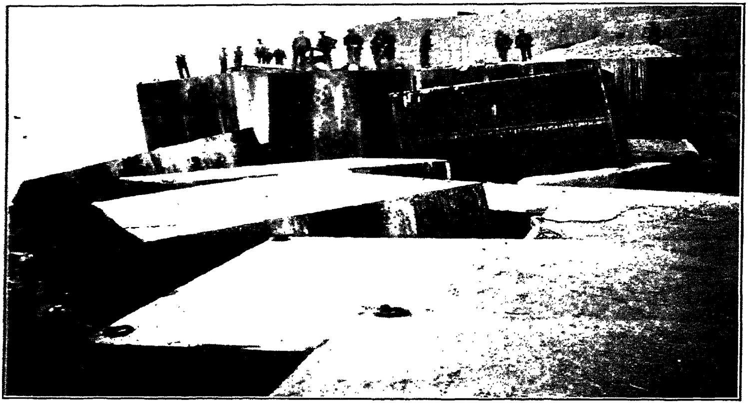

FIG. 164. — Blocks moved by storm-waves, Holyhead Breakwater, Anglesey, Wales. (Geol. Surv. Gt. Brit.)

away by the waves." The massive stones which form the vertical face of this same breakwater were shattered by storm-waves in February, 1872.

In violent storms the waves rush up inclined or even vertical obstacles and exert great force far above their usual reach. In a storm on the west coast of Scotland fourteen stones, of two tons each, were torn from their places in a lighthouse wall 37 feet above high-water mark. At Bishop's Rock lighthouse at the entrance to the English Channel, the waves tore from its place a bell weighing over 325 pounds, which was 100 feet above the sea. In October, 1912, and November, 1913, the waves broke the plate glass panes in the lantern of Tillamark Rock lighthouse, which is

132 feet above sea-level. At this same lighthouse, which is on the Oregon coast, waves of 200 feet were reported in the winter of 1902. In northerly gales the lighthouse on the Morro Castle, at the entrance to Havana harbor, has waves break over its top, which is 166 feet above the sea.*

The destructive work of the waves is much facilitated by the joint planes which are present in all rocks. These partings and the many crevices and flaws which are even more abundant in most rocks are filled with air or water in the face of a sea-cliff. The tremendous blow of a storm wave compresses the air or water in the joints, which produces a wedging action, to force out the joint-blocks. A sudden compression of air, followed by a sudden release as the wave withdraws, causes the air to expand explosively. This principle is employed in the "express rifle-bullet," which has an air-filled copper cylinder in the axis of the bullet. When the projectile strikes the victim, the air in the cylinder is violently compressed, reëxpands explosively, and tears the bullet to small fragments. Of course the blow of a wave has not a velocity comparable to that of a rifle bullet, but it suffices to cause a powerful effect of air expansion.

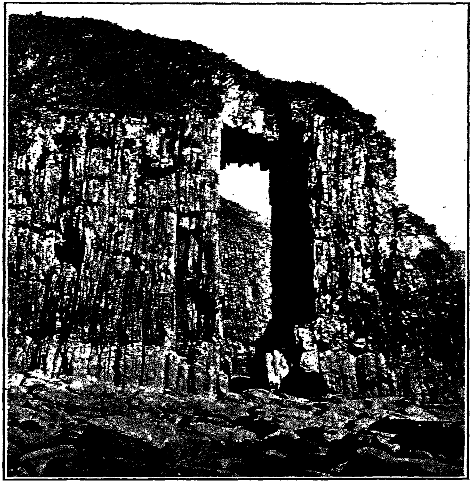

Fig. 165. — Vertical strata cut by the sea, north of Skrinkle Haven, Wales. (Geol. Surv. Gt. Brit.)

Not only is the hardness of the rock a factor in determining how rapidly a coast-line shall recede, but if the sea-cliffs are of sedimentary rocks, the attitude of the strata has an important

* Verbal communication from the late Gen. Ludlow, U. S. A.

bearing upon the erosive work of the waves, whether the beds are horizontal, vertical, or inclined toward or away from the sea. These circumstances, however, merely accelerate or retard the destructive work of the waves; that work goes on incessantly.

As in the case of a river, marine erosion is largely carried on by means of the hard material, blocks, cobbles, and gravel which the waves pick up and hurl against the cliffs and the beach, effectively bombarding them with heavy and light projectiles. There is this difference, however, between the river and the sea; without the hard material, the stream could do little work except upon soluble rocks, while the waves would cut back the coast, even though no stones and sand were present, but much more slowly.

Fig. 166. — Sea-cave in sandstone, with roof fallen. (Geol. Surv. Gt. Brit.)

In these various ways the waves attack the cliffs, battering them in storms far above sea-level, but making the principal assault at the base and undermining them. On a bold coast sea-caves are cut, which may be continued as tunnels as much as half a mile into the rocks. Sooner or later, the unsupported face of the cliff falls in ruins, leaving a mass of joint blocks, which, for a time, protect the foot of the cliff from the further attack of the waves. Eventually, however, the mass of ruins is worn away, the blocks reduced to boulders and constantly diminished in size until the sea can remove them altogether and renew the attack on the cliff.

The coast is not cut back as a straight line, but irregularly, though as a shore line approaches maturity the irregularities are gradually reduced. Not only are the rocks heterogeneous as to hardness, but the direction of incoming waves varies from point to point and it has been observed in the case of breakwaters, sea-

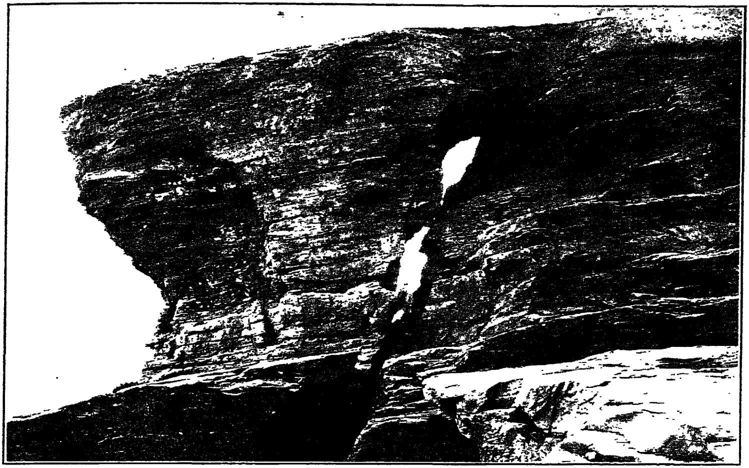

FIG. 167. — Cleft made by the sea on a fault line, near Arbroath, Scotland. (Geol. Surv. Gt. Brit.)

FIG. 168. — Roche Percée, a sea-stack at end of Gaspé Peninsula, Quebec. (Geol. Surv., Canada)

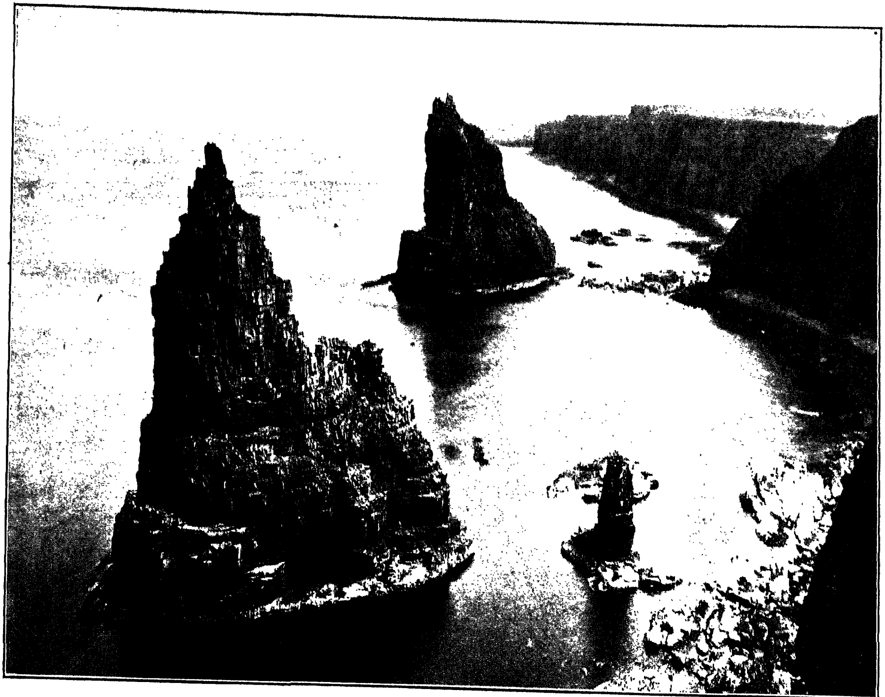

Fig. 169. — Sea-stacks of Duncansby, Caithness, Scotland. (Geol. Surv. Gt. Brit.)

walls, and other engineering structures, that, when the waves strike the wall at right angles, they are more destructive than when their course is oblique to the coast. Headlands are destroyed with especial rapidity, because they are exposed to the most violent attack and, with changing winds, from more than one side. It is therefore very common to find a wave-cut arch piercing a narrow headland and, eventually, the arch itself falls, leaving the outer buttress to stand as an isolated tower or "stack."

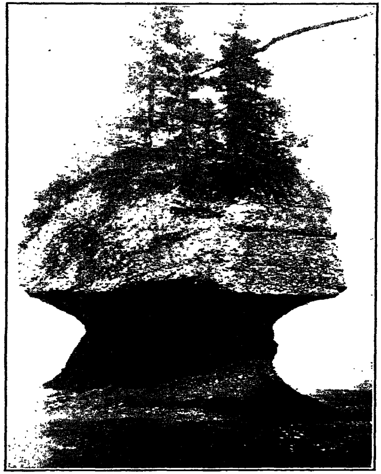

FIG. 170. — Sea-stack undercut by waves, Nova Scotia. (Geol. Surv., Canada)

On the coasts of Ireland and Scotland, such stacks are frequent, and two or three of them in line may remain to mark the retreat of the coast. Unless protected by a cap of harder rock, the tower-like stack weathers into a pyramid and, at last, the combined attack of sea and atmosphere will remove all trace of it except an under-water reef. Much that seems to be the work of the sea is really due to the atmosphere, which operates to especial advantage because of the rapid removal of débris and the constant renewal of bare surfaces of rock.

The erosive work of the sea on a rocky coast results in cutting a level platform a little below low-tide mark, which, however, is cut at a diminishing rate, because of the retarding action of the shallow water upon the waves. Whether, with diastrophic movement eliminated, the sea could completely remove a large land area is a question differently answered by various authorities, but is not likely to be of more than academic interest, because of the unlikelihood of a constant sea-level throughout such periods of time. If, on the other hand, the land is slowly subsiding, abrasion by the sea, keeping equal pace, cuts back a plain, to which there are no

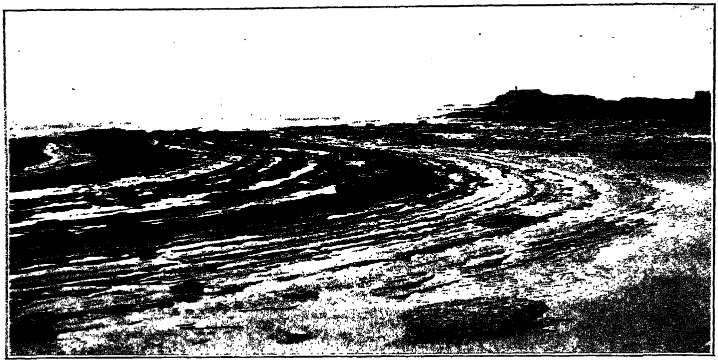

Fig. 171. — Recumbent syncline cut down by waves, near North Berwick, Scotland. (Geol. Surv. Gt. Brit.)

Fig. 172. — South coast of Spain, showing strike of dipping beds. Cliffs form dip-slopes. (O. Jessen)

limits, save those of the land itself. Such *plains of marine denudation* as were demonstrably cut down in that manner are all narrow. The west coast of Norway is bordered by an elevated wave-cut platform some 25 miles in width; on the north coast of Spain is a similar plain, some 10 miles in width, and another 60 miles wide is on the east coast of India. A narrow platform of rock above sea-level is called a *bench* and they are numerous as raised beaches. Examples of recently elevated benches on the coasts of Scotland

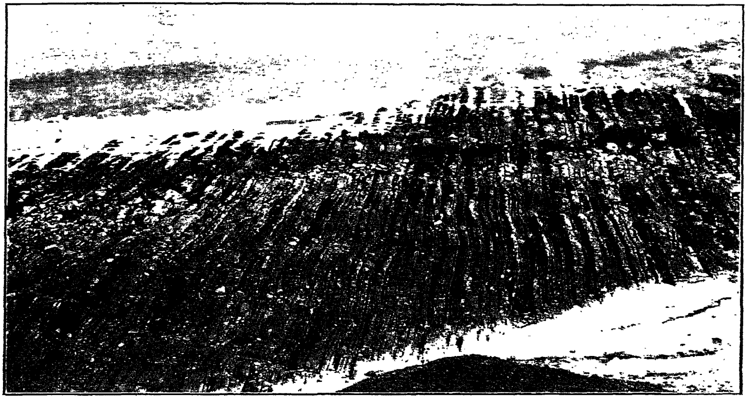

FIG. 173. — Plain of marine denudation cut across closely folded greywackes and shales, St. Abb's Head, Berwick, Scotland. (Geol. Surv. Gt. Brit.)

and Alaska are shown in the figures. It is quite possible that many plains of ancient origin may have been formed by marine erosion, as was formerly believed to be true of all plains, but it is no longer possible to prove it.

There are countless well-authenticated examples of coasts which have been cut back and lands swallowed up by the sea. Most of these are in Europe, especially on the shores of the North Sea and the Atlantic, and may be proved there because the continuous records and titles to property go back for nearly a thousand years, and the unresting waves are continuing their work of destruction today. British geologists have compiled a long list of such retreats

of the coast from which the rate per annum, or per decade, may be calculated. Lyell gave great attention to this matter and devoted to it a chapter of his *Principles of Geology*. One of the most striking cases he mentions is the harbor of Sheringham, where in 1829 the water was 20 feet deep along a line where less than fifty years before (1781) there had stood a cliff 50 feet in height. All along the east and south coasts of England, farms and villages have been washed away. On the coast of Yorkshire the rate of retreat is from 7 to 15 feet annually and in other places it is even higher. On the shores of Ireland and Scotland the stacks and underwater reefs of rock testify to the effective work of the waves.

Flat and low-lying coasts, such as are composed of sand, or, less commonly, of river mud, being usually areas of accumulation, are less subject to wave attack, but violent storms often cause great destruction, as is exemplified by the North Sea coasts and islands of Holland and Germany, which have lost much since the Middle Ages and would have lost more had not successful means of protection been devised. Much of Holland lies below sea-level and would be submerged were the dykes to be swept away. The sandy coast of New Jersey has been greatly changed in the short course of American history and the local sea walls have been entirely futile as a means of protection. More successful have been the "bulkheads" (called "groins" in England), which are constructed of heavy planking spiked to piles and carried out at right angles to the beach. These arrest the longshore drift of the sand and cause it to accumulate, thus protecting the coast.

We have seen that rivers and glaciers owe much of their abrading effectiveness to the rock fragments, large and small, which they use as implements. The abrading tools are themselves abraded, worn in characteristic manner, and reduced to fine powder in the course of time. The same is equally true of the ocean which, along shore and in the zone of breakers, is constantly grinding up the rocky materials which it tears from its shores and bed or is dropped upon the beach by the action of frost. Sea cliffs have no heaps of talus at their feet, as do cliffs on land, because even large rock-slides are speedily worn down and removed by the surf. Great blocks are rounded to boulders and these worn down into cobbles, pebbles, and sand. Other minerals than quartz and even a considerable proportion of the quartz are ground into mud and carried out to sea, even to the continental slope and deep water.

Potholes are not confined to the courses of rivers and glaciers, but are formed on rocky coasts at any point where an eddy is generated in the water.

In 1831, an English geologist, W. J. Henwood, visited the mines in Cornwall, some of which have been carried out beneath the bed of the sea, and published a graphic account of his submarine experiences, from which the following passage is taken:

"I was once, however, underground in Wheal Cock during a storm. At the extremity of the *level* seaward, some eighty or one hundred fathoms from the shore, little could be heard of its effects, except at intervals, when the reflex of some unusually large wave projected a pebble outward bounding and rolling over the rocky bottom. But when standing beneath the base of the cliff, and in that part of the mine where but nine feet of rock stood between us and the ocean, the heavy roll of the larger boulders, the ceaseless grinding of the pebbles, the fierce thundering of the billows, with the crackling and boiling as they rebounded, placed a tempest in its most appalling form too vividly before me ever to be forgotten. More than once, doubting the protection of our rocky shield, we retreated in affright."

Professor N. S. Shaler made a study of the rate of wear of granite fragments when exposed to the action of the surf on Cape Ann on the Massachusetts coast:

"The wearing action even on the larger pebbles is evident from observations which can readily be made on the masses of riprap used for the defenses of the moles which inclose the small artificial harbors. . . . Although originally of very angular forms, such as plentifully occur in the quarries, an exposure to the full beating of the waves serves even in a single year to bring about a considerable rounding of the mass. In ten years they commonly wear away to the rolled form so familiar in our beach pebbles. Under favorable circumstances, it is evident that the wear upon the pebbles amounts on the average to several inches per annum."

The beach, which is partly subaërial, partly marine, is the band, or zone, between the extreme low-water mark and the line attained by storm waves. Twice a day the lower part of the beach is covered by the flood-tide and twice a day is laid bare by the ebb, and all of it is exposed to the pounding of the surf. The undertow and backwash of the waves carry away the fine material as fast as abrasion generates it, leaving the coarser material behind to

form the beach, which, for the most part, is made of sand. Gravel and shingle and coarse sand are found on the beaches of open coasts, fully exposed to the sea, and these, where gravel is available, are bounded by a *beach wall*, built up by storm waves and above the reach of ordinary surf. Such a beach wall is the twenty-foot ridge of cobblestones near Rye, New Hampshire, figured by Professor D. W. Johnson. The boulder-strewn beach at Wing Neck, Massachusetts, in the sheltered waters of Buzzards Bay, Fig. 176, owes its large and small boulders and coarse pebbles only indirectly to wave action, for these are all derived from the glacial drift, and the weak surf has been unable to move them.

2. *Depth of Wave Action.* From the geological point of view this is a very important question. It is known that the efficiency of waves rapidly diminishes as the depth of water increases, but different observers do not agree as to the depth at which the action entirely ceases, though the discrepancy is not great. Most writers give 600 to 650 feet as the limit, and at that depth only the finest particles are moved by storm waves. In the Indian Ocean, Sian detected wave-formed ripple marks at 617 feet. Those figures seem to indicate that wave action does not extend outward in any significant way beyond the margin of the continental platform.

3. *Tidal Currents* are set up between islands and the mainland, because of inequality of level. In New York Bay, for example, the flood tide, coming from the east, enters Long Island Sound and reaches Hell Gate, the entrance to the East River, before it comes into the Bay by way of Sandy Hook. While the tide is making, water in the Sound is higher than in the Bay, and powerful currents run in that direction, and at ebb tide the movement is in the opposite direction. Very strong tidal currents run in the British Channel, because of the manner in which the tide passes around Great Britain. Countless other instances might be enumerated. The action of tidal currents may be compared to that of a reversible river, flowing in one direction while the tide is rising and in the opposite direction while ebbing. As these currents have velocities of two to eleven miles an hour, their great efficiency as scouring agents is made plain and they may excavate the sea bottom to depths of several hundred feet.

4. *Ocean Currents*, which form the great system of oceanic circulation, are produced by prevailing winds and the earth's rotation, which changes the direction of the winds themselves. The law is

that in the northern hemisphere a body moving in any direction is deflected to the right and in the southern hemisphere to the left. This applies to railroad trains and the flow of rivers as well as to winds and currents. Ocean currents, of which the Gulf Stream is a very well-known example, are too far away from land to affect the shore, but they may scour the sea floor down to great depths. The Gulf Stream, flowing out through the Florida Straits, scours the bottom so that no sediment can lie there. The *Meteor's* soundings showed a scouring action of oceanic currents in depths of 2,000 fathoms or more, when the current was narrowed between islands, and in such places the sea bottom was of bare rock. On the whole, however, the erosive action of ocean currents is of very slight importance.

B. Marine Transportation

Transportation in the sea is almost entirely the work of waves and tidal currents, for the waves set up currents of intermittent action and in various directions, offshore in the undertow, onshore in the breakers, and alongshore when the waves strike the coast obliquely. The breakers bring wreckage ashore from considerable depths and distances; pigs of lead, for instance, have been brought up from sunken ships and thrown on the beach. Wave currents are chiefly responsible for the southward drift of sand along the Atlantic coast of the United States, the southwesterly trend of which makes the waves strike it obliquely and fall off to the south. All along the east coast of Florida the beaches are of siliceous sand, which could not have been derived from the peninsula, as that is made up of limestone. The sand has been brought down from the north by "beach drift." The finer particles of mud and silt and quartz sand are spread all over the continenal shelf and slope by the action of waves and tides.

A new factor in sea transportation has lately been discovered, so lately, in fact, that it is not yet possible to say how important and widespread it may be, and that is a clear jelly, apparently of organic origin, on the sea bed in shallow water. First observed by the late C. G. J. Petersen in Danish waters, it has been observed off the coast of Massachusetts by Professors Raymond and Stetson. Several lines from the shore to ten miles out were run, taking bottom samples every mile, and the jelly was found at every station, and,

after gales, it is brought to the surface, bringing so much sediment with it as to make the water turbid. "The main significance of this material lies in its obvious importance as an agent in the transportation of sand grains. Samples of the material dried and weighed after the combustion shows that about 85 per cent by weight consists of grains of various sizes from fine sand to silt. Since only the slightest amount of current is necessary to transport this jelly, it could be widely and easily distributed without evoking the aid of any strong currents near the sea bottom. The total carrying capacity must be enormous."

Professor A. F. Buddington * has observed somewhat similar material in the bays of Alaska, and it is obvious that, if this jelly-like substance is generally, or even widely, distributed on the sea bottom, its importance can hardly be exaggerated.

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CHAPTER XVII

THE SEA — RECONSTRUCTION

No process now in operation has a wider and more significant bearing upon geology than the accumulation of sediments upon the bed of the sea, for of the accessible rocks which form the continents and continental islands very much the larger part is of marine origin. The key to the understanding of these ancient marine rocks is the study of those in process of formation at the present time. When the only part of the world geologically known was northwestern Europe, it was believed that each grand division of time was characterized by some particular kind of sedimentary rock and the names of rocks were given to periods of time. Some of this nomenclature still persists, and we continue to speak of the Coal Measures, the Chalk, the Old Red Sandstone, not as rock names merely, but also as expressions for particular ages of geological time. The conception upon which this usage was founded has long been abandoned, for sedimentary rocks of every sort have been forming from the beginning of the earth's recorded history and continue to be formed today.

All kinds of sedimentary accumulations are forming simultaneously on the sea bottom, various factors determining what kind of material shall be laid down over a given area. Of these factors the most important is depth of water, but nearness or distance of land, presence or absence of river mouths along the coast, nature of the shore, whether high and bold, or low and flat, and character of the coastal rocks and climate, are all variables which enter into the result. Large, landlocked seas, like the Mediterranean, the Caribbean, and the Gulf of Mexico, though they have oceanic depths, have deposits more or less different from those of the open ocean, a difference which is largely owing to the absence or insignificance of a tide and the reduced force of the waves. Shallow, marginal seas, which are within the limits of the continental platform, such as the European North Sea and Hudson Bay, present

another set of conditions and correspondingly modified deposits. The Baltic and the Black seas, though salt, have water which is below the normal salinity of the ocean, and their deposits, each in its own way, are different from the other bodies of salt water which are not lakes.

Each of these various types of sea has had its counterpart in the ancient history of the continents. Especially important were the *epicontinental* or *epeiric* seas, which from time to time submerged most of the continents, save Africa and probably South

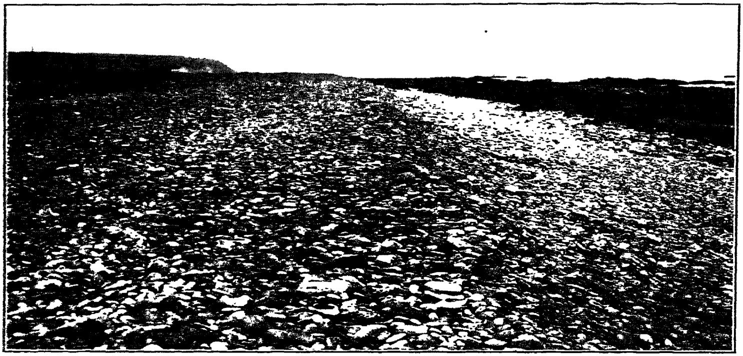

FIG. 174. — Storm-beach, Portgower, Scotland. (Geol. Surv. Gt. Brit.)

America. Not that the whole of any continent was submerged at one time, but now one region of it, now another, was invaded by shallow seas, of which Hudson Bay is a type. The deposits now forming in the Black Sea seem to explain peculiar aggregations in central New York, and that is but one illustration of many that might be given in emphasizing the need of studying existing seas to decipher the records made by those of the past.

Many surveying expeditions, sent out by various governments, have collected samples of bottom deposits from thousands of stations for sounding and dredging in all the seas of the earth. Of these the voyage of the British naval vessel, *Challenger*, though made so long ago, from 1874–79, remains the most comprehensive and important of all the exploring cruises. The recent voyage

of the German *Meteor* promises some most interesting revelations of the South Atlantic, for the sonic method of sounding employed enables the navigator to multiply the number of observations indefinitely.

Murray and Renard reported on the bottom samples collected by the *Challenger*. Their classification is as follows:

Marine Deposits

1. Littoral Deposits, between high- and low-water marks.	Gravel, Sand, Mud, etc.	
2. Shoal Water Deposits between low-water mark and 100-fathom line.	Gravel, Sand, Mud, Calcareous Accumulations.	Terrigenous Deposits, material directly derived from the land in suspension, or solution.
3. Deep-Sea Deposits	Calcareous Mud Volcanic Mud Green Mud and Sand Blue Mud Red Mud	
	Calcareous Deposits Foraminiferal Ooze Pteropod Ooze Diatom Ooze Radiolarian Ooze Oceanic Red Clay	II. Pelagic Deposits, laid down on ocean floor, material remotely derived from land.

The sediments brought into the sea by rivers, or carried out from the shore by waves and currents, are partly in mechanical suspension, partly in solution; suspended material is deposited when the water is no longer able to transport it. This mechanically borne sediment is arranged by the sorting power of the water according to the degree of coarseness and fineness of the constituent particles. This brings with it a separation according to mineral composition, for coarseness and fineness are largely determined by specific gravity and hardness, which, in turn, are the result of chemical composition. The separation mineralogically is usually imperfect, a deposit consisting of one predominant mineral and several others in smaller proportions; sometimes, however, the separation is remarkably complete. When conditions change, if only for a few hours, according to the state of the tide, coarser materials are thrown down on finer and *vice versa*. Marine deposits are thus typically stratified, though when deposition continues

long and uninterruptedly, great quantities of sediment, not obviously divided into layers, may be accumulated, such as certain massive sandstones and limestones, but this is exceptional in those areas of the sea bottom on which deposition is most rapid.

1. Littoral Deposits are laid down on the beach between low- and high-water marks and, by heavy storms and exceptional tides, somewhat above the latter. The beach wall, or ridge, of pebbles or cobblestones has already been mentioned in another connection as the construction of storm waves. Littoral accumulations

FIG. 175. — Banff, Scotland, deflection of river by storm-beach. (Geol. Surv. Gt. Brit.)

grade into continental deposits on one side and into shoal-water deposits on the other and, on the seaward side, are alternately flooded by the tide and exposed to the sun and wind twice every day. The material of littoral deposits varies in accordance with the character of the coast. On rocky shores, boulders and shingle and coarse gravel form most of the beach, though more or less sand is present, except on very steep beaches, where the backwash of the waves carries away all the finer material. Even a rocky coast may have sandy beaches, while on low, flat coasts the beaches are altogether made up of sand, which is thus by far the most widespread of all littoral deposits.

Boulders and shingle may be composed of any kind of rock, but as they are worn down by continued attrition, the greater hardness of quartz prevails and causes it to make up most of the finer pebbles and sand, while the softer minerals are ground into fine particles and swept out to sea. Locally, sands of other composition are found on a larger or smaller scale; shell sands are widely distributed in the tropics, especially on coral reefs; iron sands, concentrated grains of the heavy magnetite, as in the gold-bearing

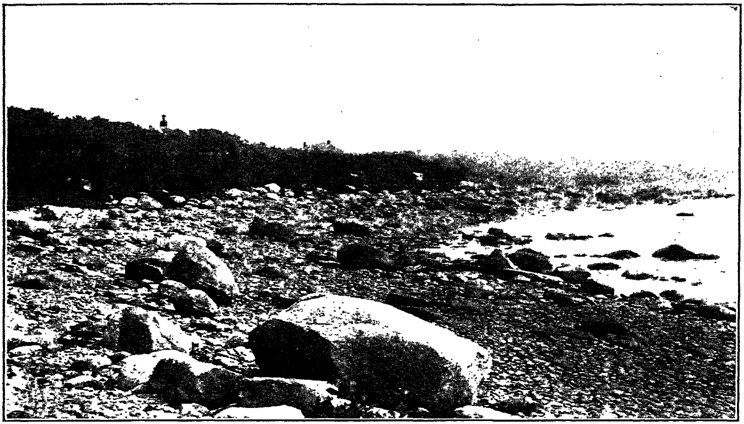

Fig. 176. — Beach at Wing Neck, Mass., with glacial boulders washed out of the drift.

beach at Nome in Alaska are not rare, and in the Bay of Naples sands of olivine, feldspar, and other volcanic minerals occur. Fine sand and mud may accumulate, even in the littoral zone, in places sheltered from waves and currents, but the material is preponderatingly coarse.

At any given time, the littoral is a narrow belt, fringing all coasts and, at present, having an estimated total area of only 62,000 square miles, but its breadth at any particular place depends upon the height of the tide and the slope of the bottom. On a very gently sloping bottom the ebb tide may expose a beach two or three

miles in width. Littoral deposits may be greatly extended in area, or increased in thickness by diastrophic movements of the coast. On a stationary shore, or one where accumulation is more rapid than a movement of depression, littoral deposits may form a broad area by building out the land at the expense of the sea. When subsidence and upbuilding go on at equal rates, great thicknesses of littoral deposits may result. Still another manner of extending the coarse beach deposits is by subsidence of the land, in consequence of which the sea submerges the land and spreads

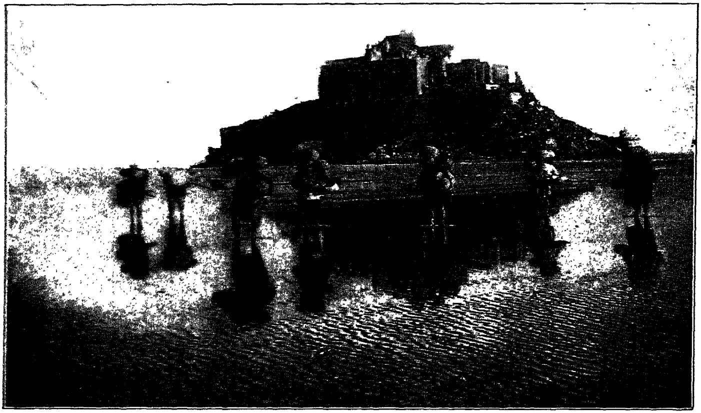

FIG. 177. — Ripple-marked sands, low tide, Mont St. Michel, France.

sheets of pebbles and coarse sand as it advances. So frequently does a new cycle of sedimentation begin in this fashion that *basal conglomerates* are a recognized feature of the incipient cycle.

Aside from the coarseness of their material, littoral deposits are apt to retain certain marks characteristic of their exceptional mode of origin. *Wave Marks* are made by waves washing up on the beach after breaking and are preserved by the deposition of thin layers of sand in the edge of the waves; such marks are made only on the beach. The same is true of *Rill Marks,* which are made by rills of water trickling over the sand or mud at ebb tide. *Sun Cracks* (mud cracks, or shrinkage cracks) are formed when

mud flats dry out in the sun and crack from shrinking. Sun cracks form on a much larger scale in the flood plains of rivers and in the mud left by disappearing playas and are more likely to be preserved than those which form in the littoral, the only marine deposits in which they are possible. *Ripple Marks* are formed by the wind, either directly, as in sand dunes, dry, sandy beaches, or snow drifts, or indirectly by first producing a rippling movement of the water,

FIG. 178. — Ripple-marked sandstone. (U. S. G. S.)

and that causes ripples in the sediment. The marks are much more common in sand, but may also be found in other kinds of material, and they are by no means confined to the littoral zone, for they occur in shallow water down to depths of 100 fathoms and more. Ripple marks occur in rocks of all geological periods and in all sorts of sedimentary rocks except conglomerates, most frequently in sandstones.

Rain Prints are little, pit-like depressions made by light showers; they have even rims when the drops fall vertically, and have one

rim raised when the rain falls obliquely before the wind. *Tracks of land animals* which walked upon soft, wet sediment, which is fine-grained enough to retain the impressions, are afterwards hardened by exposure to sun and wind. Like mud cracks, footprints are not so frequently found in marine deposits as in those laid down on the flood plains of rivers and in estuaries, because the returning tide usually obliterates them, but when they are found in association with marine fossils, they prove the littoral origin of the rocks that contain them.

It might seem incredible that such slight and evanescent marks as those made by rills and ripples, waves and raindrops, or the footsteps of animals should be preserved for ages in the solid rocks, were it not for the undoubted fact that they are actually found so often. Surfaces which were capable of retaining such impressions were those of accumulation, and each layer with its marks was somewhat hardened before the next layer was deposited upon it. When a rock carrying any of these marks is split along a bedding plane, the upper surface of a layer shows the marks as impressions and the under surface of the layer next above bears casts of the impressions in relief.

Climatic influences are not clearly marked in the littoral zone, the character of which is chiefly determined by the nature of the adjoining land and the slope of the sea bottom. Only in very high latitudes is a special character given to the littoral deposits by the activity of frost and coast ice, which makes block and boulder beaches more common than elsewhere.

2. Shoal-Water Deposits: ***a. Mechanical.*** The material of the littoral zone is carried out beyond low-water mark to distances which vary according to several circumstances. On the coasts of arid regions, such as those of Peru and northern Chile, where no rivers enter the sea and all the material of the littoral and shallow-water zones is supplied by the sea's own action upon the shore, the arrangement of coarse and fine deposits is quite regular, and gravel beds may extend out as much as ten miles from land. Waves and currents carry sediment not only away from the shore, but also parallel with it, and tend to simplify the coast line by building barriers and spits across the mouths of bays, which the waves may pile up above high-water mark, as may be seen along the eastern coast of the United States, especially on the south shore of Long Island and the coasts of New Jersey and North Carolina. The

barriers inclose shallow, quiet bays and sounds, into which streams bring sediment, mostly very fine, filling up the bays and converting them into salt marshes and eventually into land.

Much the most abundant and characteristic material of the shoal-water zone is quartz sand, which is on a gently sloping bottom and extends out to the margin of the continental shelf, becoming finer with increasing distance from land. Off the Massachusetts coast the mud zone begins at about fifty fathoms depth. Near shore, gravel may accumulate, but not when the coast is low and flat, for then there is no source of pebble supply. Wave action affects the bottom throughout the whole of the shallow-water zone, but very feebly in the deeper parts. In sheltered spots, or in deep depressions of the bottom, where the water is nearly stagnant, mud is thrown down. When the land supplies large quantities of fine sediment, this will supplant the sand on the sea floor, as it does south of Block Island, where a large triangular patch of clay invades the sandy area.

When strong tidal currents are generated, they have not only an important erosive effect, but also do much transportation and deposition. In the English Channel the tides sweep with great force, especially eastward, and they so scour the bottom that the bare rock is exposed and glacial boulders too large to be moved lie scattered over the rocky floor. The sand which the tidal currents carry along enters the North Sea and is deposited in part along the coast of Holland, and in part forms banks and shoals in the Sea.

Near shore, currents produce irregularities of stratification which are called *cross bedding* (also current or false bedding), which are very much like the variable results of wind action on a sand dune. In cross-bedded deposits the separate layers are inclined at considerable angles to the horizontal plane. This structure is due to the heaping of ridges, on the sheltered side of which sand, or gravel, is dropped in inclined layers, which frequently make up horizontal strata, the inclined layers all truncated by horizontal bedding planes which bound each stratum above and below. Cross bedding occurs in shoal water of all kinds, the sea, lakes, and rivers, wherever the bottom is frequently stirred up by currents, especially when these are of varying directions. It is most frequent in sandstones. Ripple marks are also very frequent in shallow water deposits, especially in sandstones, but not infrequent in shales and limestones.

Obviously, a great thickness of shoal-water deposits can be accumulated only upon a sinking sea bottom, for, otherwise, the water would be filled up and the shore line advanced into the sea. If the subsidence be very slow, deposition may shoal the water and extend the coarse material seaward; if it be rapid, deepening the water, fine sediment will be laid down upon coarse and the sea will encroach on the land. If the rate of deposition and that of subsidence be nearly equal, the coarse deposits will form long, narrow bands parallel with the shore.

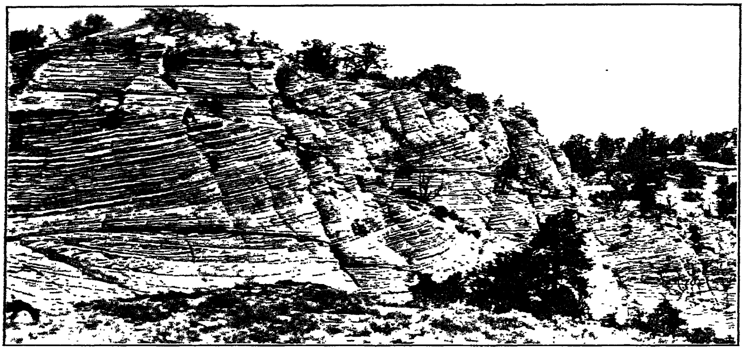

FIG. 179. — Cross-bedded sandstone, Utah. (Photograph by Hillers, U. S. G. S.)

Thus, under changing conditions, many different kinds of sediment may be accumulated in the same vertical line, corresponding to the different depths of water at the same spot. When traced laterally in either length or breadth beds of any kind may continually give way to those of another kind, either by gradual transition in the material or by thinning to an edge and interdigitating with the thin edges of other beds. Though a stratum may persist for tens or even hundreds of miles, with parallel bounding surfaces, it is a much-flattened lenticular body, or cake-shaped. Of course, strata cut off by erosion in any direction end abruptly in that direction. Interdigitation means a shifting of conditions back and forth, a succession of violent storms sweeping coarser material out to unusual depths, where it comes to rest upon finer

sediment, and long periods of calm, occasioning the deposition of fine material unusually near shore. A sandbar may be an effective barrier between two seas, or between the sea and a lake, and as the barrier is moved first in one direction and then the other, interdigitation of the strata must result. Several such instances are known among ancient rocks.

b. Organic Deposits are much less frequent in shallow water than the terrigenous and mechanical, and yet, under favorable conditions, they may be developed on a great scale. Of the favorable conditions, the most important is an abundant food supply and next to that warmth of water, for the animals and plants which give rise to organic accumulations flourish best in tropical and subtropical seas and in shallow water. Calcareous deposits are made even in the far north and extremely cold water, but on no such scale as in the low latitudes. The sea constantly derives from the land substances in solution, of which much the most abundant are calcium carbonate and sulphate; many kinds of marine animals extract the carbonate from the sea water and form it into hard parts, either as external shells or internal skeletons. There is reason to believe that some marine organisms can convert the sulphate into the carbonate.

The classes of marine organisms which have played the most important parts in accumulating calcareous material are: the Foraminifera, Corals, Echinoderms, Molluscs, and the calcareous Algæ, or seaweeds which look so deceptively like corals that they were long mistaken for them; other groups, such as the Bryozoa and certain worms, contribute extensively, but not to such an extent as those first mentioned. The Foraminifera do not accumulate with sufficient rapidity to add largely to shoal-water calcareous accumulations and will be considered in connection with deep-sea deposits. The rôle of Bacteria in forming marine deposits is not yet well understood.

1. *Mollusca.* The ordinary shellfish, or molluscs, supply a very large amount of calcareous material for the formation of shoal-water limestones, especially near the coasts and in warm, temperate, and even Arctic seas. Dead shells accumulate in great banks, frequently, though not always, mingled with more or less sand or mud. When the shell banks are below the limit of violent wave action, the shells remain entire, embedded in finer material, which may or may not be calcareous. In shallower water the

shells are pounded to fragments by the surf, making a shell sand and mud, which are then cemented into more or less compact rock. In the formation of shell banks carnivorous Crustacea and fishes play an important part, for they grind up shells, even such as are quite thick and heavy, and produce an angular calcareous sand, which may be deposited by itself or fill in the interstices of the shell banks.

The coquina limestone of Florida is an example of a recently made shell limestone (though it is forming no longer), and in the ancient rocks of the earth's crust are many immense bodies of limestone of this nature, but much more compact and dense than the

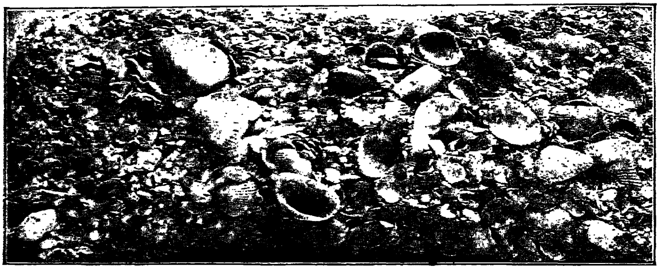

FIG. 180. — Modern shell-limestone (coquina), Florida.

coquina, which is very light, and its fragments are imperfectly cemented together. Professor R. M. Field, with several associates, has lately investigated the great flats and shoals around Andros Island in the Bahamas, which are of remarkably fine, white calcareous mud, that shows no trace of organic structure, even under the microscope. The origin of all this calcareous matter was a curious problem, whether it was a bacterial deposit, or a chemical precipitate, or whence it could have been derived. It now appears that fresh-water shells from Andros Island have been the principal source of supply and that the mud is swarming with bacteria, which, however, do not seem to have been concerned in precipitating the calcium carbonate from solution.

2. *Echinodermata.* This group of marine animals, of which the principal subdivisions are starfishes, sea-urchins, and crinoids, or sea-lilies, no longer has the importance as limestone makers which

it possessed in former ages of the earth's history. This decline in relative importance is due to the great reduction in the variety and numbers of the crinoids, which, now quite rare, were formerly immensely abundant, and many of the ancient limestones are composed chiefly of their remains. All of the echinoderms mentioned have external tests made of many thick calcareous plates and they contribute largely to the formation of marine limestones, but, at present, do not form them unassisted.

3. *Limestone Banks.* Where conditions are suitable, immense submarine banks are built up in waters of small or moderate depth

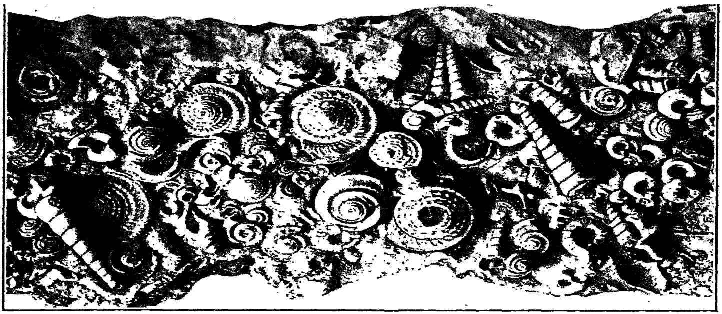

FIG. 181. — Ancient shell-limestone (Ordovician), Mo.

by the accumulated remains of all sorts of lime-secreting animals: corals, echinoderms, molluscs, worms, and Foraminifera. Excellent examples of these are to be found in the Gulf of Mexico and Caribbean Sea, the great banks along the west coast of Florida, the Yucatan Bank, and the plateau which extends from Nicaragua almost to Jamaica. On these banks the variety and luxuriance of living creatures are astonishing, myriads of animals flourishing in the warm waters and abundantly supplied with food by the currents which sweep over the banks. Innumerable echinoderms, molluscs, and calcareous worms are continually dying and leaving their hard parts on the sea floor, waves and tidal currents spread calcareous mud and sand from the coral reefs over the débris, and the accumulated mass is rapidly cemented into hard rock by the solution and redeposition of calcium carbonate.

An example of a limestone bank in moderately deep water is the Pourtalès Plateau, which extends southward from the Florida Keys in depths of 90 to 350 fathoms. "The bottom is rocky, rather rough, and consists of a recent limestone, continually, though slowly, increasing from the accumulation of the calcareous débris of the numerous small corals, echinoderms, and molluscs living on its surface. These débris are consolidated by tubes of Serpulæ, the interstices are filled by Foraminifera and further smoothed over by nullipores. . . . The region of this recent limestone ceases at a depth varying from 250 to 350 fathoms." (A. Agassiz.) It is not known how thick these modern limestones are, but an indication is given by the raised terrace of limestone in northern Yucatan, which is built of the remains of the same species of animals as those which now live in the adjoining sea. Caverns in this rock descend to depths of more than 400 feet, without reaching the bottom of the limestone.

The shallow sea around Florida is an instructive example of the various kinds of deposits which may form at the same depths, nearly the same climate, and with very similar topography of the adjoining lands. On the Atlantic side, the beaches and sea bottom are covered with quartz sand, brought down from the north by wave drift. On the Gulf side, the northern portion is fringed with mud, carried in by the many streams which cross the coastal plain; the southern portion of the sea bottom is a limestone area.

4. *Corals.* The animals of this somewhat vague and heterogeneous group are extremely varied in form and habit of growth and by no means all of them are important as limestone makers. The solitary corals, which are very widely distributed, even in the deep sea, are never sufficiently abundant at any one spot to form deposits of themselves. The corals which do accumulate in great masses, and are called by the misleading term of "reef builders," form compound colonies of hundreds and thousands of individuals, which are but partially separated from one another. The adult corals are immovably fixed to the sea bottom, but the newly hatched young are worm-like, free-swimming larvæ. When the larva has established itself in a suitable place, it develops into a *polyp*, or fleshy sack, with rows of tentacles around the mouth, and then by budding, or the partial division called *fission*, gives rise to great numbers of other polyps, which are connected by a tissue common to them all. In this compound mass is secreted an internal

skeleton of calcium carbonate, which reproduces the form of the colony and, in most forms, with cells for the individual polyps. The great variety of form in these compound colonies is determined by the manner of budding or fission and by the relative positions of the newer to the older polyps. Some of the colonies are like trees, others like bushes, some form flat plates, while others are great, dome-like masses.

The modern reef corals have a restricted distribution and can flourish only under a combination of favorable circumstances. They are shoal-water animals and cannot live at greater depths

FIG. 182. — Growth of coral on submarine cable, harbor of Honolulu. (Courtesy of the Postal Telegraph and Cable Co.)

than twenty fathoms, nor can they exist in water of which the minimum average temperature for any month is below 68° F. and warmer water is necessary if they are to thrive. The water must be clear and of normal salinity and hence they cannot live at the mouth of a river, which makes the sea-water turbid and too fresh. Currents that bring abundant supplies of food and are not too swift are favorable to the growth of the reef and the polyps flourish best in heavy surf. Briefly stated, reef corals are tropical or subtropical, marine, shoal-water animals, and their reefs are widely distributed in the warmer seas. Where they are absent, it is because one or other of the necessary conditions is lacking.

The coral polyps do not build the reef, they merely furnish material for it. The work of piling up the reef is done by the waves. The coral colonies are scattered over the sea bottom much as vege-

FIG. 183. — Great Barrier Reef of Australia, an inner reef showing the great area of coral exposed at low spring tides. (Photograph by C. M. Young)

tation is on land, growing densely in some places, sparsely in others, and not at all in certain spots. The waves, especially in storms, break up the colonies, which are weakened by the borings of many other marine animals and grind them to fragments of all sizes, just as does the surf on any rocky coast, from large blocks to the finest mud. Thus, there are formed by wave action, boulders, shingle, pebbles, sand, and mud; it is only the material that differs. The many animals that feed upon coral assist in the grinding process, both by boring into the mass and by masticating small pieces.

A great deal of the calcareous débris is contributed by the shells and tests of the many animals that live on the reef. The coral-like Algæ, the *Nullipores*, are very important contributors, while the sand made from comminuted mollusc shells often makes up half the reef. All of this material is ceaselessly ground by the waves, distributed by tides, and brought to rest in quiet waters, whether sheltered by the reef or in depths beyond ordinary wave action. After a gale along the Florida reefs, as much as two or three inches may be deposited between tides, and the sea-water will be discolored and turbid for miles around the reefs. The water dissolves and redeposits $CaCO_3$ in the interstices, cementing the débris into rock, which may become very hard, especially if exposed to the air at low tide.

Several varieties of coral rock are formed, which correspond in everything but material to the clastic deposits made on any ordinary rocky coast. In one variety, the standing and intact colonies are buried and filled in with débris and inclosed in solid masses. Rock of this kind has many and deep holes penetrating it, where the colonies are not in contact and the fine material has failed to reach. Coral conglomerate, or breccia, is a mass of cemented coral pebbles or angular pieces. Reef rock is the dense and solid mass formed by the cementing of the fine débris which accumulates in quieter, or deeper water. Even under the microscope, reef rock often shows no trace of organic structure, a proof that absence of such structure is no reason for denying the organic origin of a limestone. On the beach is formed a curious rock, called *oölite* (*i.e.*, egg-rock) from its resemblance in appearance to fish roe. This is formed by the deposition of concentric shells of $CaCO_3$ from solution around a minute sand grain or other nucleus. Thus little spherules are generated and cemented together into a solid rock.

Fig. 184. — Great Barrier Reef of Australia, a small reef in open water, showing abundance of living coral exposed at low spring tides. (Photograph by C. M. Young)

The upward growth of corals ceases when the reef extends a little above low-water mark, but the waves continue their work and build a platform, upon which they establish a beach of calcareous sand. The sand may be further piled up into dunes by the wind and solidified by the cementing action of rain water. According to circumstances, the platform may be either an extension of the shore or a new island, like the Florida Keys.

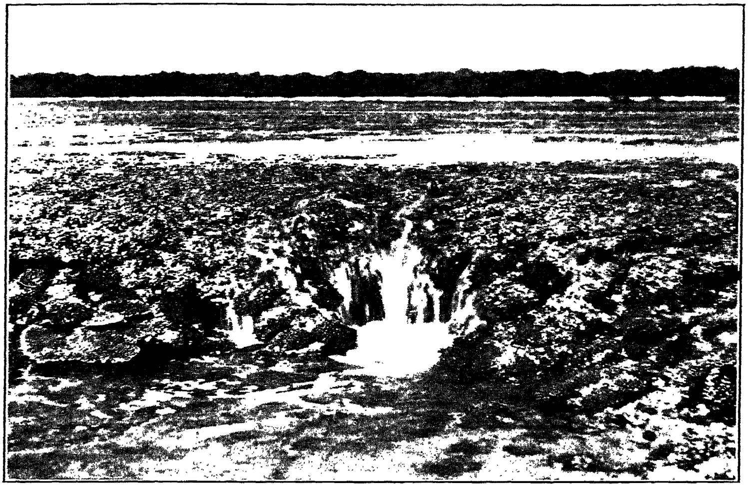

FIG. 185. — Northwest island of Capricorn group; reef exposed at low-water spring tides. (Photograph by C. M. Young)

Coral reefs are classed according to their relation to the shore and are of three kinds: (1) Fringing reefs are those attached directly to the land, though the part above water may be at some distance from the shore and separated from it by shallow water with coral bottom. The width of a fringing reef is determined by the slope of the sea bottom, being narrower on a steep grade, broader on a gentle one. (2) Barrier reefs are farther out from the shore, which they follow in a roughly parallel course and from which

they are separated by a broad and often deep channel. The distinction between the two kinds of reefs is not at all a radical one, for the same reef may be fringing in one part of its course and a barrier in other parts. Some of the existing reefs are on a very large scale. A barrier reef runs parallel to the north shore of Cuba for nearly its whole length. That of New Caledonia in the Indian Ocean is 400 miles long. The largest known example is the Great Barrier Reef, which extends, with some interruptions, for more than 1,200 miles along the northeastern coast of Australia, from which it is separated by 20 to 80 miles. The breadth varies from 10 to 90 miles, though it is mostly a submarine platform, and but little of the reef rises above the surface of the sea; the sea face rises, in some places, more than 1,800 feet above the bottom of the ocean.

(3) Atolls are coral islands of more or less circular shape, often remarkably regular, and usually inclosing a central lagoon, which is almost always connected with the sea by one or more openings in the reef. Atolls, of which there are great numbers in the archipelagoes of the South Pacific, frequently rise abruptly from the profoundest depths of the sea and, in view of the very limited depth at which reef corals can live, the manner in which atolls have been formed is a subject of much debate. There is every reason to believe that the deep sea atolls are built up from extinct volcanic cones which have been truncated by the waves, and such volcanic platforms would be within the limits of coral growth. A reef that is more than 125 feet thick must have been built upon a slowly sinking base, the rate of subsidence not exceeding the rate of growth. It is not necessary, however, to suppose that all atolls were made in this manner. Some have been raised and show the reef resting on a platform of a different kind of limestone; others, again, to all appearance, were built on a stationary foundation. Essentially, the problem is the same for great thicknesses of any kind of shoal-water deposits.

Coral reefs in shallow water frequently have gentle exterior slopes, but those which rise from the deep sea have very steep faces, as much as 65°, and thus geologically ancient reefs, when embedded in other rocks, may appear, in cross-section, as lenticular areas or steep-sided masses of limestones, in which stratification is very obscure or wanting, surrounded by well-marked beds.

The borings put down in the island of Funafuti in the Ellice

group of the South Pacific have led to much controversy. The boring penetrated to a depth of 1,114 feet and encountered only organic limestone, but corals are very subordinate in its make up. Professor J. S. Gardiner believes that the boring penetrated talus rather than the actual reef. Much the most abundant elements are calcareous Algæ, and then Foraminifera, corals coming only in the third place. Another boring was put down from the deck of a ship into the bottom of the lagoon, where the water is 100 feet deep. At the bottom is a layer, more than 100 feet thick, of the calcareous seaweed *Halimeda opuntia*, mixed with numerous Foraminifera. Down to 245 feet were the same materials mingled with corals, and at that depth the boring was stopped by encountering masses of typical reef corals, and their presence at such a depth is evidence of sinking.

Nearly all of the marine organisms which secrete the calcium carbonate in the form of calcite contain more or less magnesia, and the proportion of this rises with the temperature of the water. Among echinoderms, for instance, the percentage of magnesia rises from 6 per cent in cold water animals to 14 per cent in those which live in warm water. When the shell, or test, is of aragonite, there is practically no magnesia. Marine limestones, as accumulated by the kinds of animals which make such accumulations, must contain considerable quantities of magnesia. This is strikingly confirmed by the analyses of the drill-cores brought up from the Funafuti reef. From the surface downward, the magnesia content increased to 16 per cent at a depth of 26 feet; then the percentage declined to a little over 1 per cent at 600 feet. Then, in the next 40 feet, it suddenly rose to 26 per cent and increased to 41 per cent at the bottom. Dolomitization has been repeatedly observed in connection with coral reefs and is attributed to the action of magnesium chloride from sea water concentrated by evaporation.

Though in many reefs, perhaps in all, calcareous Algæ contribute more material than do the corals, it is nevertheless true that in order to have a reef, the conditions of depth and temperature must be those favorable to reef corals. According to Gardiner the Algæ are essential, but corals are dominant below four to six fathoms. Even in the tropics, the west coasts of Africa and South America have no reefs, because the cold currents coming from the Antarctic Sea lower the temperature too far for coral growth. The reefs of

Bermuda, which are built upon the foundation of a truncated volcanic cone, as has been proved by borings, contain hardly any true corals. Various lime-secreting animals and calcareous Algæ contribute to the formation of the reefs, which are principally composed of the tubes of marine worms belonging to the genus *Serpula*.

c. Chemical Deposits. It is not known how large a rôle is played by chemical precipitation in the sea, but probably it is not great. Rivers which bring in large quantities of $CaCO_3$ in solution may so overcharge the sea with this substance, for salt water will dissolve but little of it, that more or less is deposited in the neighborhood of land, binding the sand into rock. This occurs at the mouth of the Rhone in the Mediterranean and on the coast of Asia Minor, where large areas of modern sandstone and conglomerate have been formed in this manner. On the coast of Brazil are some remarkable sandstone reefs of recent date; from a distance the reef at Pernambuco (more properly Recife) looks just like an artificial wall and acts as a breakwater to protect the inner harbor. These reefs are cemented by the solution and redeposition of the calcium carbonate of shells in the sand; below a depth of 10 feet, the consolidated reefs rest upon loose sand.

Professor J. E. Marr, of Cambridge, points out the resemblance of marine deposits in their mode of arrangement to those of a gigantic lake, except, of course, those made in the abysses of the deep sea. The littoral and shoal-water deposits he groups together as "the belt of variables," with the general succession, from the shore outward, of gravel, sand, and mud. Followed parallel to the coast, the sand belt is frequently interrupted by areas of mud or banks of calcareous material, due to bottom-living organisms, which constitute the "benthos." This variability is due to the fact that on the continental shelf currents and wave action make themselves felt to the bottom, stirring up the sediments, while eddies arising from tide rips throw down fine silt. These considerations apply better to an island group like Great Britain, with its violent and confused tidal currents, than to the broad, simple features of the east coast of the United States, south of Maine. There the belts of shallow-water deposits are less subject to interruption, and the clay area south of Block Island is exceptional, though off the Massachusetts coast, mud encroaches on the continental shelf and is found at depths of 50 fathoms or less.

On the continental slope is what Marr calls the mud zone, with

outer and inner mud lines, the boundaries toward the shoal-water sand on one side and the deep-water organic oozes on the other. Sir John Murray, in proposing the term *mud line*, applied it only to the outer, or deep-sea, side of the mud belt.

3. Deep Sea Deposits. According to Murray and Renard the deep sea begins at the margin of the continental shelf and therefore usually at the 100-fathom line, but by no means always.

1. Deposits on the Continental Slope. Soundings show that from the submerged margin of the continental platform there is a more or less steep descent to the floor of the ocean basin. Generally this slope of the platform is at an angle of 13° to 15°, but may be as steep as the side of an Alpine peak. The characteristic deposit of the continental slope is *mud*. The term is a convenient though not a very precise one; it is applied to an agglomeration of mineral particles in an extremely fine state of subdivision, but, for the most part, not decomposed, though mud contains a varying proportion of matter in a colloid state. Much of the material is a fine quartz flour, so fine that a distinction between mud and sand is rather one of the size of grain than of composition, but there is also an admixture of pulverized minerals softer than quartz, feldspars, augite, hornblende, mica, and very often some clay. In attempting to classify the muds, we find two that are distinctly different in appearance and composition: calcareous mud and volcanic mud. The others are distinguished by color, a seemingly trivial character and yet significant. Most of the material derived from the land, and therefore called *terrigenous*, is laid down upon the continental shelf, but the finer particles are carried farther out and subside in deeper and quieter water. A considerable quantity of the finest sediment long remains suspended in sea-water, especially in the cold polar seas, but the particles are too sparse to give the least appearance of turbidity.

1. *Blue Mud.* The materials of this deposit are mostly, but not exclusively derived from the land. Calcium carbonate is almost always present, 7 per cent on the average, but it may be as much as 25 per cent; it is mostly supplied by the microscopic shells of Foraminifera. Siliceous organisms are present also to the amount of 3 per cent and are principally the tests of diatoms and radiolarians and the spicules of siliceous sponges. Glauconite is found in nearly all the samples, but in small quantity. The blue color of the mud is due to sulphide of iron and the organic matter which prevents

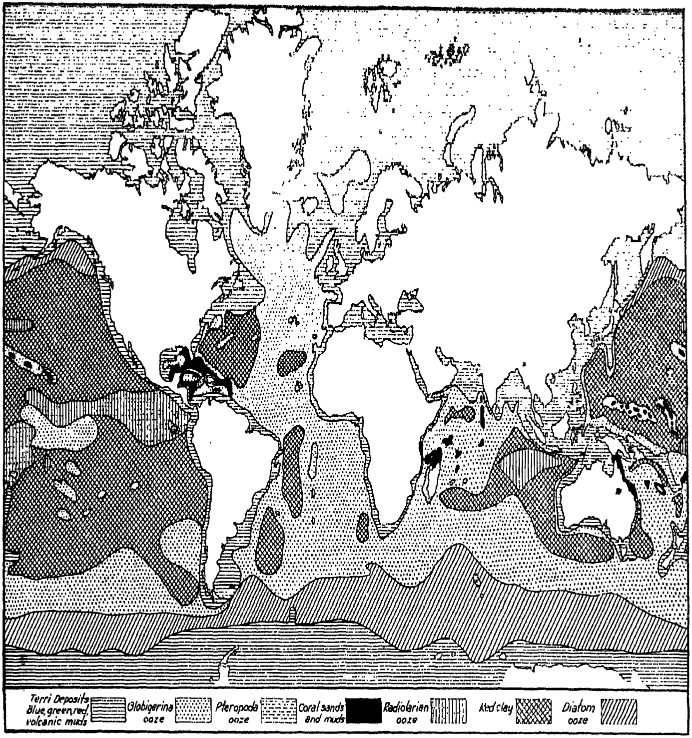

FIG. 186.—Map of modern marine deposits. (L. Collet, with slight modifications reported by the S. S. *Meteor.*)

the oxidation of the sulphide, which otherwise would turn to limonite, the hydrated ferric oxide.

Of all deep-sea deposits of terrigenous derivation, blue mud has the widest distribution; its areal extent is estimated at 14,500,000 square miles. It fringes nearly all coasts in a relatively narrow band and covers the bottom of inclosed basins such as the Arctic and Mediterranean seas. In depth it ranges from 125 to 2,800 fathoms, though little of it is known to occur at such great depths.

2. *Red Mud* is found chiefly on the Atlantic coast of Brazil and in the Yellow Sea of China; it is a warm-country product and its red color is due to the Fe_2O_3 of laterite, of which great quantities are brought to the sea by the Amazon and Orinoco rivers. So far as at present known, red mud covers but a small area of the sea bottom, but when the continental slope has been more fully investigated in tropical seas, probably much more of it will be found. In red mud Foraminifera are abundant, Radiolaria very scanty.

3. *Green Mud* is much the same in character as the blue mud, but contains a larger proportion of glauconite grains.

4. *Green Sand* is granular, being made up of glauconite grains and internal casts of the shells of Foraminifera. The green sands are found in shallower water than the mud and a deposit now forming off the coast of Georgia and the Carolinas is within the 100-fathom line. Murray's estimate for the area of the green muds and sands was 1,000,000 square miles, but since then the *Meteor* has discovered new areas off the coasts of Africa and South America in depths of 50 to more than 1,000 fathoms. At certain periods in the earth's history, green sands were much more widely spread than at present.

5. *Calcareous Mud* is derived chiefly from coral reefs, from which the finest débris is washed down the steep slopes to depths of all degrees. These muds represent the ground-up shells and tests of all the many kinds of lime-making organisms that abound on and near coral reefs. Such muds are local and are not carried far from the source of supply.

6. *Volcanic Mud.* In the waters around volcanic islands are deposits of fine mud derived from the attrition of volcanic rocks. As many such islands rise from the profoundest depths, their submarine slopes are very steep and the muds produced in the active zone of surf are easily carried down to great depths. Mingled

with the mud are considerable quantities of clay derived from the decomposition of volcanic minerals and of the calcareous material of organisms.

II. Pelagic Deposits. The material of the deposits made in the oceanic abyss is, for the most part, derived only indirectly and remotely from the land. Part of it is volcanic débris in an advanced state of decomposition, the remainder consists of material brought into the sea in solution and is extracted from the water by animals and plants. Terrigenous material, other than volcanic, plays but a small part in abyssal deposits, but it is not altogether absent. Off the west coast of Africa, for instance, the wind carries such quantities of sand from the Sahara into the sea that a sandy area has been formed on the ocean floor. Here, however, the continental shelf is very narrow and deep water is close to land. The *Meteor* found an unexpected amount of terrigenous sediment in the deep sea of the South Atlantic and discovered that there were definite relations between the size of particles of this sediment and the topographic relief of the ocean floor in any particular area.

The pelagic deposits accumulate at an inconceivably slow rate, especially in the case of the oceanic red clay. The term *ooze* is employed for mud-like deposits which, under the microscope, are seen to be made up of the shells and tests, in more or less whole and unbroken condition, of animals and plants. Two of these, foraminiferal and pteropod, are calcareous and two, the radiolarian and diatom, are siliceous. The diatoms are microscopic plants, the other groups are animals.

1. *Foraminiferal Ooze.* The Foraminifera are minute specks of jelly and belong to the simplest and most primitive of animals, the Protozoa. Despite their extreme simplicity of structure, these infinitesimal creatures have the power of secreting exquisitely beautiful shells of calcium carbonate and in endless variety of form. The species which contribute extensively to the formation of the ooze are those which live in infinite multitudes at the surface of the ocean. At the present time the most abundant genus is *Globigerina*, from which the deposit is often called *Globigerina ooze.* These surface Foraminifera thrive best in warm seas, and they follow the warm currents into quite high latitudes. The animals are short-lived and multiply with great rapidity, their dead shells, falling to the bottom in all depths and "like a continual snow

storm," are found in all sorts of marine deposits; they contribute extensively, as has been shown, to the material of coral reefs, and the green sand contains a high percentage of them. Near shore, terrigenous materials preponderate so largely, that the foraminiferal shells make up but a very small proportion of the deposits.

The proportion of Foraminifera increases in bottom deposits with the depth of water and when 30 per cent or more of a given bottom sample is made up of these shells, it is classed as a foraminiferal ooze. Other lime-secreting organisms, corals, echinoderms, molluscs, calcareous sea-weeds, etc., contribute more or

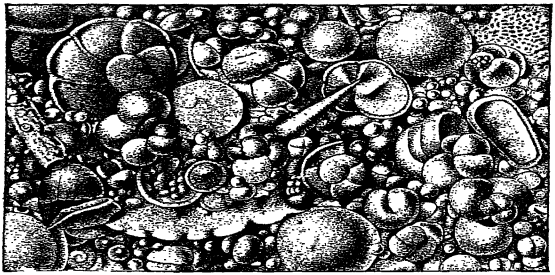

Fig. 187. — Globigerina ooze, × 20. (Agassiz, after Murray and Renard)

less to these oozes, which are purest and most typical in medium depths of sea, far from any land, where they are white in color and may have a percentage of $CaCO_3$ as high as 90 per cent. Nearer land, the slight admixture of terrigenous minerals give a tinge of gray, pink, brown, or other color to the ooze. Below the depth of 2,500 fathoms the proportion of $CaCO_3$ is much diminished, because of the solvent action of the carbon dioxide which increases in quantity with the depth of water. The delicate shells are attacked and dissolved, and below 2,900 fathoms they disappear.

The foraminiferal oozes, it is estimated, cover rather more than 49,500,000 square miles of the deep-sea bottom and are especially developed in the Atlantic, though they are largely present in all seas except the polar ones; their range in depth is from 400 to 2,900 fathoms.

2. *Pteropod Ooze.* The two molluscan groups known as pteropods and heteropods abound at the surface of tropical and sub-

tropical seas, but their delicate and fragile shells are not found on the bottom in depths greater than 1,500 fathoms, because the shells are dissolved. At depths of 700 to 1,500 fathoms in tropical seas globigerina ooze passes gradually into the pteropod accumulation, and because of the limitation of depth, this ooze is usually found on submarine rises far from land. Originally found by the *Challenger* only in relatively small areas of the North Atlantic, later exploring vessels have much extended this range. H. M. S. *Britannia* found large areas of pteropod ooze on the borders of the Great Barrier Reef of Australia and in shallower parts of the sea

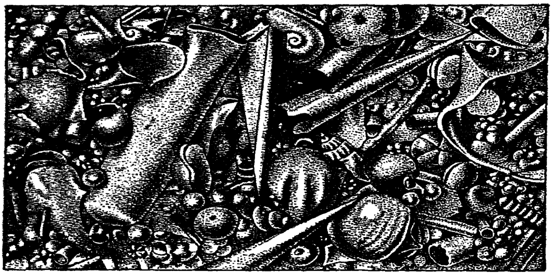

FIG. 188. — Pteropod ooze, × 4. (Agassiz, after Murray and Renard)

between Australia and New Zealand and the Ellice and Union groups of islands and also around the Marquesas. It is estimated that this ooze covers 1 per cent of the bed of the Pacific, while the foraminiferal ooze covers 18 per cent. Pteropod ooze occurs also on the median rise of the South Atlantic; its areas everywhere are small and scattered.

3. *Radiolarian Ooze.* The Radiolaria, like the Foraminifera, are microscopic, one-celled Protozoa, which form the most exquisite and lace-like tests of silica. The tests are either hollow and much perforated and spiny spheres, or rods radiating from a center, or modifications of these plans; it is this radial symmetry which suggested the name for the group. These animals live both at the surface and at the bottom of the sea. Radiolarian tests may be detected in marine deposits of all sorts, in both deep and shoal water, but, *under present conditions*, it is only in the profoundest depths of the sea that they occur in sufficient quantity to give

character to the deposit. When 20 per cent or more of a bottom sample consists of radiolarian tests, it is called a radiolarian ooze, though clay and volcanic minerals make up most of the deposit.

This ooze has, as yet, been found only in the Pacific and Indian oceans, and is entirely absent from the Atlantic, though it is found as a series of strata in the island of Barbados. In the Pacific it extends from the coast of Central America westward for 150° of longitude, and another large area is in the southern Indian Ocean northwest of Australia. The estimated area covered by radiolarian ooze is 2,290,000 square miles, ranging in depth from 2,350 to 4,475 fathoms.

Because of the rarity of unquestioned deep-sea deposits in any part of the land, unusual interest attaches to two occurrences of radiolarian ooze above sea-level. One of these is the long-known presence of the ooze in late Tertiary strata in the island of Barbados and the other is in the East Indies. The Banda Sea, to the southwest of New Guinea, is ringed with islands having a radiolarian ooze consolidated into a firm rock. Radiolarian cherts occur in the Alps, but geologists differ concerning their mode of origin and as to whether they are deep-sea deposits.

4. *Diatom Ooze.* The microscopic unicellular plants known as diatoms thrive in fresh, brackish, and salt water. Their beautifully sculptured cases, or frustules, of transparent flint are found in many marine deposits, but in small quantities. On the floor of the Antarctic Sea is an immense belt of diatom ooze which encircles the globe and has an area estimated at nearly 11,000,000 square miles. Beside the Antarctic area there is a narrow band that encircles the North Pacific from Japan to Kamchatka, the Aleutian Islands, Alaska, and British Columbia. In addition, small scattered areas have been unexpectedly found in the western Pacific between Guam and the Philippines.

5. *Oceanic Red Clay.* Excepting only the depths where radiolarian ooze is found, the profoundest abysses of the oceans, far from any land, are floored with a deposit of red clay, which, though varying much in composition and appearance, is yet of quite uniform character. At these great depths, the foraminiferal shells have almost all been dissolved by the carbonated sea water, but about 6 per cent of calcium carbonate remains in the clay, diminishing in quantity with increase of depth. In the less profound abysses the red clay grades into foraminiferal ooze, the number of shells

increasing until the ooze-like character is attained. Radiolarian ooze is principally composed of the red clay in which at least 20 per cent of siliceous organisms are accumulated. In some areas the clay is not red, but made chocolate brown by the oxide of manganese.

The red clay is derived from the decomposition of volcanic materials, especially pumice, which floats upon water for months and is carried long distances by the ocean currents, eventually becoming water-logged and sinking to the bottom; particles of volcanic glass and undecomposed minerals are common in the clay. The inconceivable slowness with which this is formed is shown by the fact that an appreciable part of it is made up of particles of iron from the meteorites that reach the earth from outer space. That the bones and teeth of marine animals which have long been extinct should still lie unburied and exposed on the ocean bed is another proof of the infinite slowness of deposition of the clay.

Of all the pelagic deposits, the oceanic red clay is the most widely extended, covering an estimated area of 51,500,000 square miles, four-fifths of it in the Pacific. In depth, the observed range is from 2,225 to 3,950 fathoms.

On inspecting Professor Collet's map of modern marine deposits (Fig. 186), certain broad facts of distribution stand out with great clearness. It is first necessary to guard against the erroneous impression which the Mercator's projection always gives by greatly exaggerating the size of the polar regions. The vast basin of the Pacific is floored with a deposit of red clay, which is nearly bisected by a band of radiolarian ooze. The southern portion of the Pacific bottom is covered by foraminiferal ooze, which floors nearly the whole Atlantic and Indian oceans, with some subordinate areas of red clay, the largest of which in the Atlantic is in the North American Basin, lying off the east coast of the United States. In the Indian Ocean the red clay area is a very irregular one to the west of Australia. The *Meteor* reports that "in the southern part of the Argentine Basin the *Globigerina* ooze, hitherto mapped, is not present, though the organisms themselves were abundantly observed. The muds have Antarctic components." The extent of the foraminiferal ooze almost equals that of the red clay. Diatom ooze encircles the earth in the Antarctic Sea, in a continuous belt of very irregular width, and also fringes the North Pacific. Terrigenous deposits, most of which are blue muds, come third in

the extent to which they cover the sea bottom on the shelf and slope of the continents. The blue mud covers the whole bottom of the Arctic Sea and all the northern bays and marginal seas, the Mediterranean, the northern part of the Indian Ocean, and the great platform from which rise the islands of the Malay Archipelago. All the continents are fringed with a relatively narrow belt of terrigenous deposits, sand, and blue mud. Thus the bottom of the deep sea is almost entirely covered with three kinds of deposits: red clay, foraminiferal ooze, and blue mud. Diatom ooze is nearly as extensive as the mud, but the other kinds of terrigenous and pelagic deposits, red mud, green mud, and sand, coral and volcanic muds, and pteropod ooze have a very subordinate rôle.

6. *Chemical Deposits.* A certain, but as yet unknown, amount of chemical activity is at work in the deep sea. Glauconite, which forms the principal part of the so-called green sand, is a chemical deposit, but the derivation of the potassium which it contains is not understood. In the blue mud, decomposing organic matter reduces sulphates to sulphides, which are afterwards decomposed by carbon dioxide. The sulphur of the sulphates dissolved in sea water is fixed in the mud as ferrous sulphide (FeS), while carbon dioxide takes the place of sulphuric acid in forming calcium carbonate. Iron and manganese are among the most widely disseminated metals and frequently form nodules in the red clay, deposited in concentric layers around a nucleus. Analysis shows that the nodules are composed of the hydrated oxide of manganese, mixed with variable quantities of limonite and clay. The radiolarian rock from the islands of the Banda Sea contains nodules of manganese. Finally should be mentioned the phosphatic concretions, irregular lumps composed chiefly of calcium phosphate, dissolved and redeposited from organic material. These concretions occur along lines where marine organisms, especially fishes, die in great multitudes, owing to sudden changes of temperature, occasioned by the meeting of warm and cold currents.

The important inference to be drawn from the study of marine deposits now in process of accumulation is this:

By far the greatest portion of the marine rocks which now form the land are such as are deposited in water of small and moderate depth and that rocks of pelagic origin are very rare on the land.

Effects of Climate on Marine Deposits. The shoal-water deposits of cold and temperate seas differ but little, being preponderatingly

of sand, with some gravel; limestones do occur, but infrequently and on a small scale. Deep-sea deposits differ in the two zones, in that blue mud is distributed all over the bottom of the Arctic Sea, while foraminiferal ooze and oceanic red clay are absent from both of the polar seas, and the Antarctic has an encircling belt of diatom ooze. The tropical seas have red muds and a great development of calcareous accumulations. Pelagic deposits are essentially the same in both temperate and tropical seas, being determined chiefly by depth of water. In these regions the bottom of the deep sea is covered very largely by foraminiferal ooze and oceanic clay. As climatic differences are less extreme in the sea than on the land, the effects are less distinctly shown in marine than in continental deposits.

Estuarine Deposits

An estuary is the mouth of a river which is invaded by the sea because of a depression of the coast. In such bodies of water the tide often scours with much force in the channel while depositing sediment on the flats and shallows. There are many estuaries on the Atlantic coast of North America, Chesapeake and Delaware bays; the lower Hudson and St. Lawrence are tidal estuaries, as is the lower Thames in England. The water in an estuary ranges from brackish at the upper end to full salinity near the mouth and is unfavorable to animal life, for only a limited number of marine animals and a still smaller number of fresh-water ones can thrive in brackish water.

Estuarine deposits are, in general, much like those of the sea, but they are usually of finer grain for a given depth of water; mud is abundantly thrown down, especially in the more sheltered spots, with sand and even gravel in more exposed situations. The sands are apt to be cross-bedded, but with horizontal layers made at slack water. Extensive mud flats often line an estuary, especially if the range of the tide be great. On these flats, exposed to sun and air at low water, sun cracks will form in hot, dry climates and these with rain prints and the tracks of land animals, will be preserved when the next incoming tide, advancing too gently to scour the hardened surface of the mud, deposits a fresh layer of silt upon it. In pluvial climates the mud does not dry sufficiently between tides to crack or retain impressions. If the estuary is the opening of a large river, considerable deposition of river sediments may take

place when the stream is in flood, producing an alternation of fresh and brackish water beds.

Though estuaries are not favorable to the organisms of either fresh or salt water, deposits made in them may contain great numbers of individuals of a few species that can adapt themselves to brackish water. Oyster shells may accumulate in great banks and diatoms may multiply to an incredible degree, as they do in certain Baltic harbors. On the other hand, estuaries often preserve the remains of land animals and plants, which are carried in by streams and buried in the mud flats.

THE CONSOLIDATION OF SEDIMENTS (DIAGENESIS)

The processes of erosion, transportation, and deposition, so far considered, result only in the accumulation of masses of sediment, regularly arranged in beds, but loose and incoherent and, in the case of subaqueous deposits, saturated with water. If the hard stratified rocks of the earth's crust — sandstones, slates, and limestones — are to be explained by modern processes of sedimentation, it must be shown how these incoherent masses are consolidated into firm rocks, comparable to the ancient strata. This is not difficult; hard rocks of modern date are not uncommon, but in them only one mode of diagenesis has been observed. Other methods which, there is every reason to believe, are effective in nature, are beyond the reach of observation and must be inferred from the results. It is a roughly general rule that the higher the geological antiquity of a sedimentary rock, the harder it is, but there is no real relation between hardness and antiquity; the mere passage of time is impotent to consolidate sediments. On the other hand, the older a rock is, the more vicissitudes has it passed through, of pressure, heating, cementing, etc., and the more likely it is, therefore, to be thoroughly consolidated. Of course, there is the converse process of rock decomposition and disintegration, but that affects rocks at and near the surface which are slowly but steadily removed by denudation, exposing new rocks that had previously been protected. The various methods of diagenesis are as follows:

1. *Consolidation* by *Cementing* is probably the most widely acting means of solidifying sediments and to it all the modern instances are due. Very generally sediments are traversed by water which carries in solution substances that, when deposited in

the interstices, bind the loose grains into solid rock, just as Portland cement, when mixed with water, sand, and gravel, sets into the hard and solid concrete. The commonest binding substances in solution are the carbonates of calcium and iron ($CaCO_3$, $FeCO_3$) and SiO_2. Calcium carbonate is the most accessible and the most soluble of these and is therefore most frequently the binding agent in recent rocks. This is true of the rocks forming in and around coral reefs, in the limestone banks, such as the Pourtalès Plateau, the modern sandstones made off the mouth of the Rhone in the Mediterranean and on the coasts of Asia Minor and Brazil. Hard sandstone dredged out of the harbor of Marseilles contained coins of the English King Henry V.

Ferrous carbonate ($FeCO_3$) exposed to the air oxidizes to Fe_2O_3, which is a very strong cement, and when deposited in loose sand makes the hard and durable ferruginous sandstone. In Florida the water from chalybeate springs binds the sand into a very ancient-looking sandstone, but the inclusion in this rock of the bones of modern Indians shows how youthful a rock it is. The deposition of silica in the interstices of sand has also been observed, where the original sand grains can hardly be detected with the microscope, the rock appearing to be a mass of crystalline quartz grains. A binding effect appears also to be induced by chemical reactions within the mass of sediment itself, as when volcanic ash solidifies into a tuff by being mingled with water.

2. *Consolidation by Weight of Sediments.* When deposited on a subsiding sea-bottom, sediments often accumulate to enormous thicknesses and the bottom portions must tend to consolidate from the pressure of dead weight. True, this consolidation cannot be observed in operation, but may be inferred from the analogy of known facts.

3. *Consolidation through Heat.* When molten magmas come into contact with other rocks and send out highly heated vapors and solutions, they completely reconstruct the invaded rock, metamorphosing it, as will be shown in a subsequent chapter. Short of metamorphism, however, heat hardens the rock as, no doubt, it does when the lower part of very thick sediments is invaded by the interior heat of the earth.

4. *Consolidation by Compression* acts so gradually and at such depths below the surface that its operation cannot be observed, but its effects are plain. As will be shown in a subsequent chap-

ter, stratified rocks, which were originally formed in horizontal beds, have in many regions and in all mountain ranges been compressed and crumpled into folds, fractured and dislocated by tangential or horizontal compression. Pressure by weight of sediments is static, compression is dynamic, and the more intensely compressed any rock has been, the harder it is. There are great areas of sedimentary rocks which retain their originally horizontal position and yet have been thoroughly hardened without compression, probably by cementing. Certain very ancient marine sediments, which have never been disturbed and have been elevated but little above the sea, remain as loose and incoherent as when they were first formed.

The parallel is now complete between the loose sediments which may today be observed in process of accumulation and the solid stratified rocks which form most of the land surfaces. For each and all of these ancient rocks there may be found a counterpart in the sediments now being laid down, and it may be confidently affirmed that the ancient strata were formed in the same way as the modern ones. Every rock contains the record of its own history.

Summary of Rock Destruction and Reconstruction

Destructive Action. The surface of the land is everywhere attacked by the universally present atmosphere at a rate which differs much in different regions, depending upon climate, elevation above sea-level, and the resistant power of the rocks. The rain chemically decomposes the rocks, converting them into soil, and mechanically washing this soil to lower levels and into the streams. Frost shatters the rocks into smaller and smaller fragments. In arid regions the extreme changes of temperature break up the rocks much as does the expansive force of freezing water, while the wind transports immense volumes of sand and dust, which cut and carve and wear away the exposed rocks. Underground waters, especially when heated, do an important work of solution and decomposition, and, under favorable circumstances, cause the dislodgment of great masses of earth and rock in landslips and rock-slides. Rivers excavate valleys and serve as the great agents of transportation, bearing the waste of the land to the sea, and glaciers do similar work in a highly characteristic manner. The sea cuts into its coasts by the action of waves, deepening its

bed in shallow places by tidal currents, and in the case of a slowly sinking land may plane down great areas to a flat, gently sloping surface. Animals and plants add an important quota to the general work of destruction.

The annual waste of the land at the present time is estimated at 20 cubic kilometers (Penck), and, in past times, an incalculably great amount of material has been removed from the land. The Appalachian Mountain system has thus lost thicknesses of rock which vary in different regions from 8,000 to 20,000 feet, and it is altogether probable that the average waste of all the continents amounts to several thousands of feet. The figures given for the basins of the Mississippi and Ganges show that such waste implies enormously long periods of time. Assuming that the estimates of geological time made in accordance with the data of radioactivity are to be accepted, it follows that the rate of land-waste at the present time is unusually high. The length of the various periods is too great for the amount of measurable denudation, if the present rate of removal had been the average for past ages.

Reconstructive Processes. The destructive agencies supply a great mass of material, of which, *under existing conditions* of climate, topography, etc., about one-half is arrested in its journey to the sea and the remaining half completes that journey; the former moiety constitutes the continental deposits, and the latter moiety the terrigenous marine deposits.

Continental deposits are of great variety, and their nature is determined chiefly by the factors of climate and topography. In the arid and desert regions we have great accumulations of drift-sands, of angular talus, of flood-plain and playa sands and muds, which are characteristically sun-cracked and more or less impregnated with various salts. Deposits from salt lakes, such as salt, gypsum, soda, borax, etc., are confined to arid climates and are not formed in humid climates. In pluvial climates of the temperate zones, rain-wash, deep soils, lacustrine deposits from fresh-water lakes, and river deposits on flood plains and in channels are characteristic. In such climates sun cracks do not form over great areas, as they are largely prevented by the dense covering of vegetation. Peat bogs are the seats of great vegetable accumulations, especially in the cooler and moister regions. In the polar regions, glacial deposits and frost talus are the principal modes of accumulation, and in high mountains these also penetrate deep into the

temperate and even the tropical zones. In the tropics we find extremely deep soils, which contain or are made up of the red laterite, and surface deposits of iron oxide and chemically formed limestone are extensively made. Immense masses of river alluvium gather in interior basins, but vegetable accumulations are less abundant than in temperate lands, and lakes are not common in the tropics. The absence of lakes, however, is not determined by temperature, but by the antiquity of land surfaces. It cannot be inferred from the fact that only half of the annual land-waste finds its way to the sea, that such should be the proportion between continental and marine deposits among ancient rocks, for a transgression of the sea over an ancient land surface deeply buried under continental deposits would rapidly rework the latter into marine deposits. At present, we observe that material derived from the land and in mechanical suspension laid down in the sea is distributed by the waves and currents, sorted into layers according to the fineness of the material and, more or less incompletely, according to its mineralogical composition. The most important factors which determine the character of the deposit at any given point on the sea-floor are the depth of water and the topography and elevation of the adjoining land. The coarser materials, gravel and sand, are laid down upon the beach and in shoal water, the sand generally extending to the 100-fathom line, while on the continental slope are deposited the various muds, and on the floor of the ocean basins the organic oozes and the oceanic red clay, derived chiefly from the decay of volcanic minerals. Limestone banks are formed by the extraction of the dissolved lime-salts through organic agencies, a process which goes on most extensively in warm seas of shallow and moderate depth. Climatic differences also have their effect upon marine deposits, but less markedly than in the case of the continental accumulations. The loose sediments accumulated on land or under water are, under favoring conditions, consolidated into hard rocks, thus making the parallel with the ancient sedimentary rocks complete, and finishing the cycle of destruction and reconstruction from rock back to rock. All these various kinds of deposits, continental and marine, are forming simultaneously, but one kind of deposit does not gather indefinitely at one point, except on the deep-sea floor. Conditions change so that one kind of material is laid down upon another and many different beds occur in the same vertical section. Each of these beds records the

conditions at that point for the time during which a given bed formed the surface of the lithosphere. The changes now in progress give a key to the record contained in the rocks, a key which does not, however, unlock all the mysteries. It remains to study the ways in which the rocks are arranged and the disturbances to which they have been subjected.

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CHAPTER XVIII

STRUCTURE OF LARGE STRATIFIED ROCK MASSES — FOLDS

This is the subject of Structural, or Tectonic Geology, which is sometimes defined to include and sometimes to exclude the igneous rocks. As the latter have already been considered from the structural point of view (Chap. IV), the present chapter will deal with the stratified rocks only and will describe the arrangement of the beds in great masses, both before and after they have been disturbed and changed from their original positions. Structural geology, however, is much more than description; explanations must be found for the arrangement and mode of occurrence of the strata and, so far as possible, the data yielded by the study of dynamics must be called upon to explain the structures. This can be done in a partial degree only, for many geological processes are beyond the reach of observation, either because they are so slow or because they operate at such depths within the earth as to be inaccessible.

In attempting to explain the facts of structure, it is necessary to reason from effect to cause and this cannot always be done with confidence, because it often happens that a given structure may be referred with equal probability to different agencies. Out of a number of possible explanations, to select the one that actually produced the result, is by no means easy and often causes great differences of opinion. In no division of the science is there so much debate and uncertainty as in tectonics. It is often very difficult to ascertain the facts and still more so to find the rightful explanation of them.

In this, as in all the other provinces of the science, the historical point of view is dominant. Not only is the purpose of the study to ascertain agencies which have produced the structures, and the manner of their operation, but also the successive steps by which the structures originated, the order of their occurrence, and their

geological date. They may thus be fitted into their places in the universal history of the earth, which it is the main problem of geology to write.

Though stratified rocks cover more than nine-tenths of the earth's surface, they form but a small fraction, in thickness, of the earth's crust, relatively little more than the paper which covers a globe one foot in diameter. If the entire series of them were present in any one place, they would have a maximum thickness of some thirty miles, but no such place is accessible, if it exists at all. The areas of greatest sedimentary accumulation have always been the shallower parts of the sea, while the regions which have been land for ages may not only have had no additions to their surfaces, but have lost immense thicknesses of rock through denudation. The profound depths of the ocean have always been the seat of excessively slow sedimentation, and thus the thickness of the stratified rocks must vary greatly from point to point, a variation which has been much increased by the irregularities of diastrophic movements of elevation and depression. If the stratified rocks had always remained in their original attitudes of horizontality, it would be impossible to investigate any great thickness of them. The deepest natural trenches, such as the Grand Cañon of the Colorado, extend only to depths of 10,000 feet or less, and the deepest borings do not extend so far into the earth's crust. In many places the strata have been folded or tilted and then truncated by erosion, so that their *edges* form the surface of the ground, and thus great thicknesses of them may be examined without penetrating into the interior. In crossing the State of New York, from Lake Ontario to the Pennsylvania border, many thousands of feet of strata are exposed, all gently inclined, or *dipping*, to the south (Fig. 277) and in regular succession. No artificial opening is needed to examine this great thickness of beds; the ordinary irregularities of the ground are sufficient. There is a similar succession of tilted beds across the south of England from Wales to the North Sea, a cross section which made possible the beginnings of historical geology and is of preëminent importance in the development of the science. By the coördination of many such sections in the different continents, approximately the entire thickness of stratified rocks is being brought to light.

Stratification, or division into beds, or layers, is the most characteristic feature of the sedimentary rocks. The study of the sedi-

mentation that is now in progress shows (p. 229) that stratification is owing to the sorting power of wind or water, by which heterogeneous material is arranged in more or less homogeneous beds, each bed consisting predominatingly of a single mineral and separated from the bed above and that below by planes of division, or partings. Not only do modern sedimentary deposits show this division into more or less parallel layers of stratification, but the sediments of all geological ages, including the most ancient known, are likewise stratified.

A single member, or bed, of a stratified rock is called a *layer*, and extremely thin layers are known as *laminæ*. If the layers are seasonal and repeated indefinitely, they are called by the Swedish term *varves*. Each layer, or lamina, represents an uninterrupted deposition of material, while the divisions, or partings between them, named *bedding planes*, are caused by longer or shorter pauses in deposition, or to a change, if only in a film, of the material deposited. A *stratum* is the assembly of layers of the same mineral composition which occur together and are bounded above and below by layers of different material; a stratum may thus consist of one layer or many. There is much looseness in the use of the term and frequently layers and strata are employed synonymously. The passage from one stratum to another is generally abrupt and indicates a change of conditions, either in depth of water or in the character of the material brought to a certain spot. So long as conditions remain the same, the same kind of material will be deposited in a given area, and thus immense thicknesses of similar material may be accumulated. To maintain such constancy of conditions, the depth of water must not be materially changed and hence the bottom must subside at the nearly same rate as that at which the deposit is made.

Usually, a section of thick rock masses shows continual change of material at different levels. In Fig. 189 is shown an actual section through certain strata in Beaver County, in the coal regions of western Pennsylvania, which registers several changes in the conditions of sedimentation at the same point. At the bottom is a coal seam (No. 1), the carbonized and consolidated vegetable matter which was accumulated in an ancient peat-bog. Next came a depression of the bog, allowing a rapid current of water to flow over it and deposit fifteen feet or so of gravel mingled with coarse sand (No. 2), and reduced velocity eliminated the pebbles and brought

about the accumulation of sand above the gravel. These deposits so shoaled the water that a second peat-bog was established, resulting in the formation of a second, thinner coal seam (No. 3), a proof that the second bog did not continue so long as the first. A renewed subsidence flooded the bog with quite deep water, in which about 12 feet of fine silt was thrown down, now consolidated into a shale (No. 4). An opposite movement of upheaval rendered the water shallower and permitted the deposition of about twenty-five feet of sand and clay, later consolidated into an argillaceous sandstone (No. 5), and this so filled up the water that a third peat-bog (No. 6), which continued much longer than the earlier ones, was formed, and in this was accumulated the mass of vegetable matter which resulted in the formation of a six-foot seam of coal with a very thick under-clay. Again depression allowed water to cover the bog and the depression continued *pari passu* with the deposition of gravel by a swift current until 70 feet of the gravel, now a conglomerate, were laid down.

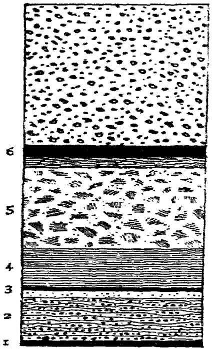

FIG. 189. — Section in coal measures of western Pennsylvania. (White)

This, or any similar section, points to a vitally important inference, upon which the whole fabric of historical geology rests. This inference is that the successive layers were laid down, one upon another, in such a manner that the *order of superposition* counting from below upward, *is the order of succession in time*. The bed first laid down, in other words the oldest bed, is necessarily the one at the bottom, and the last formed bed is the one at the top and the intervening layers are of intermediate age, each one later in date than the bed upon which it lies, older than the one which lies upon it. In violently disturbed regions, when the strata are overturned, or when lower ones are thrust over higher ones, the order of succession in the section is not that of formation, but this discrepancy is only apparent. It is easy to show that such departures from the true order have been brought about subsequently to the deposition of the beds; they have never been seen in undisturbed or moderately disturbed strata. That the order of superposition in

a series of beds not violently disturbed should be the order of their relative age is, indeed, a self-evident proposition; it could not be otherwise. This is the reason that in geological sections the strata are numbered and read from below upward.

In this fashion, the succession of strata records the changes which were in progress while those strata were being deposited. Whether the beds in the section illustrated in Fig. 189, other than the coal seams, were laid down in fresh water, or in salt, by a lake, a flooded river, or the sea, there is nothing, in so limited a view, to decide, except such fossils as may be found in the clastic sediments. Somewhat similar changes in the material and character of marine deposits may be brought about through the lowering of the adjoining lands by means of denudation. This diminishes the velocity of the streams, which, in turn, changes the character of the sediments that the rivers carry to the sea.

There is no trustworthy way of determining the length of time required for the formation of any particular stratum or series of strata, but it is clear that different kinds of beds accumulate at very different rates. The coarser material, conglomerates and sandstones, were piled up much more rapidly than the finer-grained shales and limestones, so that equal thicknesses of different kinds of beds accumulate with very different degrees of rapidity. To put it in another way, very different thicknesses of different sorts of beds may represent nearly the same lapse of time. The Lower Cretaceous limestones of Mexico, which are 10,000 feet thick, are approximately the equivalents in time of the 600 feet of Potomac clay in Maryland. Comparing like strata with like, we may say that the thickness of a group of rocks is a rough measure of the time required for their formation, and that very thick masses require very long periods, but the estimation of geological time is made by methods very different from measuring the thickness of strata.

Change in the character of strata takes place not only vertically, but also laterally, since no stratum extends across a continent. Bodies of water are subject to frequent changes of depth, character of bottom, and other circumstances. Such changes would seem to have always taken place, as is indicated by the subaqueous rocks which now make the land. Sometimes strata may persist very evenly and with uniform thickness over vast areas and, in such cases, the bedding planes are sensibly parallel and the stratification is said to be *regular*. In many cases the changes in thickness

and character of strata are rapid and the beds are plainly lenticular in shape, thickest in the middle, thinning to the edges; then the bedding planes are distinctly not parallel and the stratification is called *irregular*. Figure 190 is an unusual example of rapid horizontal change; the two sections are taken only twenty feet apart in continuous beds. The difference in thickness of the lignite seams and the limestones and sandstones which separate them is very striking. The aggregate thickness of the lignite is much greater in the left-hand column than in the right, which has a greater thickness of limestone.

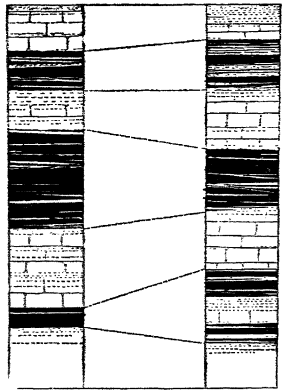

FIG. 190.—Parallel sections near Colorado Springs, Col. (Hayden)

The minuter details of structure in the stratified rocks, such as cross bedding, ripple and rill marks, rain prints, the tracks of land animals, also give valuable information as to the conditions in which the strata retaining such details were laid down.

Concretions, or *Nodules* are formed after the deposition of the beds in which they occur; they are balls or lumps of a material differing more or less from that of the including stratum. They are not pebbles which are antecedent to the layer that contains them, but were formed subsequently, as is shown by the planes of stratification, which often pass through a nodule without interruption, and fossils are sometimes found partly within and partly without a concretion. In shape, concretions vary greatly, from almost perfect spheres to grotesque aggregates, but always of rounded, never of angular, form. Very often a foreign body, such as a fossil, forms the nucleus of the nodule, which is in concentric layers around the nucleus, but such layers are not always present and the nodule may be homogeneous. A *septarium* is a nodule divided internally by radial cracks subsequently filled by the deposition of some mineral from solution.

The formation of concretions has not been satisfactorily explained; evidently, the material of which they are composed was originally disseminated through the layer and subsequently con-

centrated, but how this is effected is not known. The commonest concretions are those of clay in many kinds of rocks, flint, and chert in limestone and ferruginous cements in brown sandstone.

FIG. 191. — Concretions in Laramie sandstone, exposed by weathering.

DISPLACEMENTS OF STRATIFIED ROCKS

Most of the stratified rocks which form the visible and accessible parts of the land are of marine origin, and the fact of their occurrence on land is proof that they have been displaced, at least relatively, from their original positions. Marine strata are found on the tops of high plateaus, or lofty mountains, many thousands of feet above sea level, as well as in low-lying plains but little raised above the sea. Originally, strata must have been nearly or quite horizontal, for such is the operation of gravity. A deep and quiet fall of snow gradually buries the minor inequalities of the ground and forms a level sheet and, in the same manner, sediments are spread out over the sea floor in nearly level layers, first covering up irregularities. This original horizontality is not perfect and departures from it are frequent, but, on a large scale, these departures are very slight and conspicuous ones are of only small extent.

Examples of such original deviations from horizontality are: (1) The foreset beds in deltas. (2) Alluvial cones, or fans, have steeply inclined layers. (3) Sandy beaches often have considerable inclination, as much as 8 per cent, and newly deposited layers conform to this slope. (4) On a large scale, the sediments of the continental shelf have a slight inclination away from the land and those on the continental slope a considerably steeper one. These slight original inclinations of strata are called *initial dips* and may have an important bearing upon subsequent displacements.

Diastrophic movements were classed as epeirogenic, with vertical displacements, either simple uplift, or warping (see Chap. IX), and orogenic, in which the movement is tangential. Vertical displacements may leave strata in their original horizontal altitude or may tilt them into inclined positions, may leave them intact or fracture and dislocate them by faulting. Tangential movement results in compressing the beds into a series of curves called *folds*. Uplift, warping, folding, and faulting are thus the ways in which the diastrophic movements of the earth's crust affect rocks of all descriptions, but it is the stratified rocks with which we are, at present, concerned.

As a preliminary to the study of displacements, a few terms must be defined, terms which antedate geology, having arisen to meet the needs of men who worked in the rocks, miners and quarrymen, and geologists were glad to adopt them, for they serve the purposes of the science equally well.

Dip is the angle of inclination which a tilted bed makes with a horizontal plane and is measured in degrees. The line, or direction, of dip is the line of steepest inclination of the dipping bed and is expressed in terms of compass bearing. For example, a bed may have a dip of 15° to the northwest. The angle of dip is measured by an instrument called a clinometer, of which there are many forms. In making a geological map, or in tracing the underground extension of surface beds, the measurement of dips is an indispensable preliminary.

Strike is the line of intersection of a dipping bed with a horizontal plane and is therefore always at right angles with the line of dip. An ordinary roof, taking only one side of it, may represent a dipping bed, then the ridge pole, or any line on the roof parallel with the ridge pole, will be the line of strike. Another illustration

would be a slate held in an inclined position, as the dipping bed, and lowered into a vessel of water till partially submerged. The surface of the water is a horizontal plane and so the wet line on the slate will be the strike (Fig. 172). As the strike must always be at right angles with the line of dip, it will change its direction, as the latter changes, but will be a straight line so long as the

Fig. 192. — Claggett shales, tilted, Mud Creek Gap, Mont. (Photograph by Stanton, U. S. G. S.)

direction of the dip remains constant. The Appalachian Mountains in Pennsylvania form a sweeping curve of nearly 90° from the Delaware River to the center of the state; the directions of dip change from northwest and southeast to west and east and the strike follows the curve. Horizontal strata have no dip and therefore can have no strike; both terms apply only to tilted or folded beds.

Outcrop is the line along which a stratum cuts the surface of the ground and horizontal beds may crop out on the sides of hills or valleys or on a plain, if the surface of the latter does not coincide

with that of a stratum, but cuts obliquely across the bedding. In the case of tilted or folded beds outcrop and strike are coincident when the surface of the ground is level. The direction of dip remaining constant, the rougher and more irregular the surface of the ground, the more do outcrop and strike diverge. For a given kind of surface relief, outcrop and strike differ more when

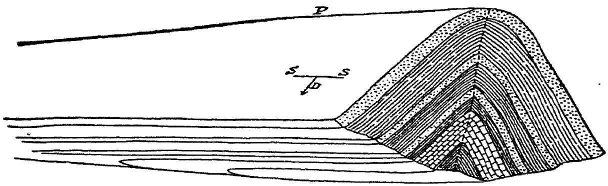

FIG. 193. — Model of anticline. *P*, axis pitching to the left; *S S*, line of strike; *D*, line of dip. The dotted line is the plane of the axis. (Willis)

the angle of dip is low than when it is high, for when the strata are vertical, outcrop and strike again coincide and the more nearly the strata approach verticality, in other words, the higher the angle of dip, the more nearly do the two lines approach each other. When looked at broadly, as on a small-scale geological map, outcrop and strike are much the same and follow the same general course, the sinuosities of outcrop balancing one another.

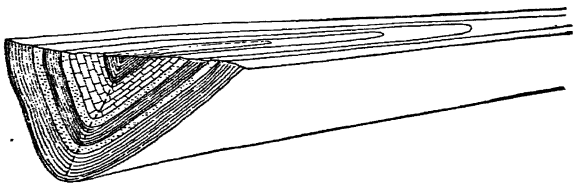

FIG. 194. — Model of syncline. (Willis)

Folds are curved strata, usually in a succession of upward and downward bends in parallel series, but which may, in rare instances, occur singly. They are found in great variety of form, but, fundamentally, there are only two types, anticlines and synclines, one of which is the inversion of the other. A third type, the monocline, is usually called a fold, but it would be better to

use the term *flexure* for it, as it is produced in an entirely different way from the true folds and is more nearly allied to faults.

1. The *Anticline* is an upward fold, or arch, of strata, from the summit of which the beds dip downward on both sides. The curve of the arch may be broad and gentle, or sharp and angular, or anything between the two. The line along which the fold is prolonged is called the *anticlinal axis* and may be scores of miles or only a few feet in length. The fold may be represented by an ordinary roof, which represents the two sides, or limbs, of the anticline, while

FIG. 195. — Single anticline, upright and symmetrical, Peace River. (Geol. Surv., Canada)

the ridge pole will be the axis. The same illustration was used above to explain dip and strike and serves equally well for both; it seems to have been first used for the anticline, almost exactly one hundred years ago, by H. de la Beche, who, in spite of his name, was an eminent English geologist. Whether long or short, the fold eventually dies away, sloping down into the undisturbed area of the beds; its summit is therefore not perfectly horizontal, but gently or steeply inclined, as the case may be, and this inclination is the *pitch* of the fold. According to the length of the axis and the steepness of the pitch, the intact anticline is either short and domelike, or long and cigar-shaped.

FIG. 196. — Rainbow Arch, an anticlinal ridge, Carcajou River. (Geol. Surv., Canada)

FIG. 197. — Anticlinal arch, north fork of the Potomac, W. Va. (Photograph by Darton, U. S. G. S.)

2. The *Syncline* is the complement of the anticline, the strata being curved downward into a trough-like valley and dipping from both sides toward the bottom, which is the synclinal axis. As in the anticline, the axis may be long or short, with gentle or steep upward pitch and forming long, narrow, canoe-shaped valleys or oval, even circular basins. In section the syncline may be shallow and widely open or may have steep sides and angular bottom.

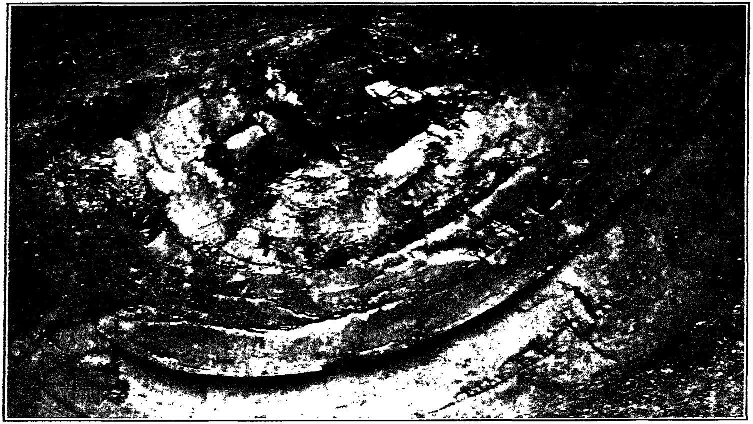

FIG. 198. — Syncline in Utica Shale, near Upton, Penn. (Photograph by Stose, U. S. G. S.)

3. *Domes* and *Basins* are special cases of anticlines and synclines. The dome is an anticline and the basin a syncline in which the axis is reduced nearly or quite to zero. In the former case the dome and basin have an oval ground plan and in the latter case they are circular. Basins and domes are more apt to occur singly than the elongate folds. The Black Hills of South Dakota are a single, oval dome, which rises suddenly from the plain and is not connected with any other fold. The dome has been deeply dissected by erosion, so that its structure is fully displayed. The term *basin* is used in different senses and it is necessary to distinguish

between the basin of folding and the basin of erosion; only the form is common to both, the structure is entirely different.

Anticlines and synclines usually occur in parallel series, each pair of anticlines connected by a syncline. At one end of the folded belt several axes may converge and unite in a single fold; sooner or later they all die away, the pitch of a fold coinciding with the dip of the beds.

4. *Geanticline and Geosyncline.* No terms have departed more widely from their original meaning than these, and it will be very advisable to return to the sense in which they were originally employed by Professor J. D. Dana, who proposed them. Ordinary folds affect the strata at the surface and for moderate depths beneath. It is quite impossible that the earth's crust, as a whole, should be involved in folds of such small amplitude. The crust, however, is involved in certain great folds, which are therefore called geanticlines and geosynclines; the latter of these is much the more important and was originally defined by Dana thus: "Lateral pressure from contraction is a force of indefinite power. . . . It acts horizontally, or very nearly so. . . . Its first effect is to produce great upward and downward bendings in the crust: geanticlinals and geosynclinals." In a footnote he adds: "The bendings are bendings, not of strata, or formations, but of the earth's crust covered with its strata, folded or not folded." The terms may thus be legitimately applied to the deep, sediment-filled troughs of interior basins, as Dana's definition says nothing of sea bottoms.

5. *Anticlinorium and Synclinorium,* likewise proposed by Dana, have been much misunderstood. "Such a mountain range begun in a geosynclinal, and ending in a catastrophe or displacement and upturning, is . . . a *synclinorium,* it owing its origin to the progress of a geosynclinal." "An upward bend of the crust, or geanticlinal, is of itself an elevation and such an elevation is an anticlinorium." In many geological works, including the former editions of this book, these terms are defined as compound folds made up of many anticlines and synclines; if the combined effect were an upward bend, it was mistakenly called an anticlinorium, if downward, a synclinorium. Dana derived the *orium* from the Greek "oros," a mountain. Professor Collet defines the term as follows: "*A geosyncline is a long marine depression, which may be the result of compression or of stretch* (Argand). *A geosyncline is*

situated between two continental masses and is destined to be filled up by sediments, while geanticlines develop in it." Other modifications have been proposed by various writers, but in this book Dana's original definitions will be adhered to.

Folds may be classified in several different ways: (1) according to the relation of the opposite limbs to each other; (2) by the relative thicknesses of the folded strata on the limbs and in the plane of the axis; (3) by the degree of compression. Additional categories are employed, but are hardly necessary here.

FIG. 199. — Asymmetrical anticline, partly cut down by the sea. Harbor Saundersfoot, Wales. (Geol. Surv. Gt. Brit.)

(1) According to the first method they may be distinguished as follows:

(*a*) *Upright* or *Symmetrical Folds* have the two limbs of the fold dipping at the same angle in opposite directions, the plane of the axis is vertical and bisects the fold into equal halves.

(*b*) In *Asymmetrical* or *Inclined Folds* the opposite limbs have different angles of dip; the plane of the axis is oblique and divides the fold into more or less dissimilar parts and the fold is inclined to one side.

(*c*) *Overturned Folds* are those in which one limb has been pushed over past the perpendicular and are also called *inverted*.

(*d*) *Recumbent Folds* are so far overturned that they rest upon the side and one or both limbs are nearly or quite horizontal. In

FIG. 200. — Anticline and syncline, inclined folds, St. Anne's Head, Pembroke, Wales. (Geol. Surv. Gt. Brit.)

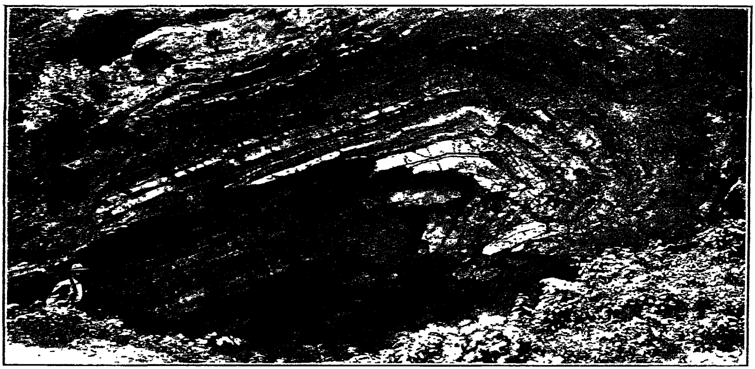

FIG. 201. — Overturned anticline, Panther's Gap, Va. (Photograph by Darton, U. S. G. S.)

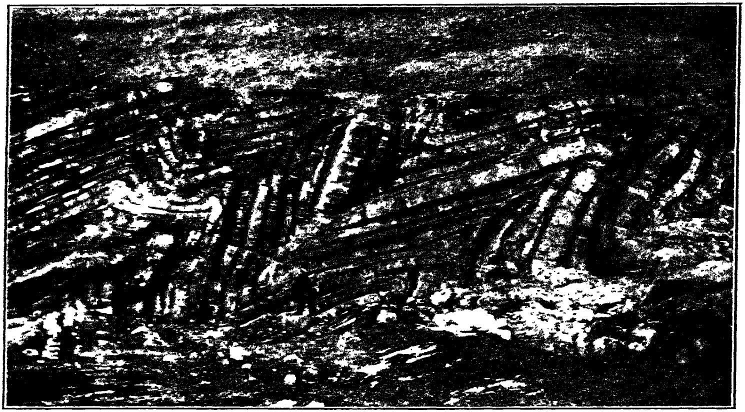

FIG. 202. — Contorted beds of limestone, Lough Shinney, Ireland. (Photograph by Prof. S. H. Reynolds)

FIG. 203. — Recumbent folds, Rusey Beach. (Geol. Surv. Gt. Brit.)

a recumbent fold the proper order of succession of the beds is reversed and if the crest of the anticline be removed by erosion, the result may be very deceptive.

(2) The second method of classifying folds deals with the relative thickness of the beds on the limbs and in the plane of the axis, and gives two types.

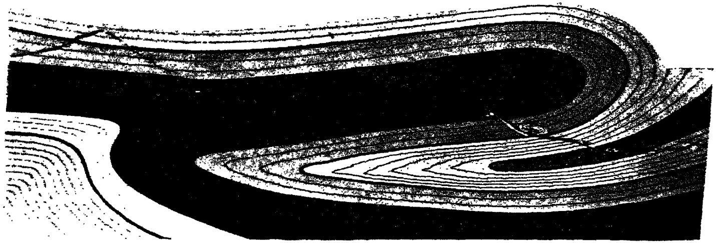

FIG. 204. — Model of recumbent Alpine fold.

(*a*) *Concentric Folds* have their strata of unchanged thickness and each bed is uniformly thick, unless there were differences in its parts before folding. In a concentric series there is a line of maximum curvature, the curves diminishing upward and downward from this line, so that the folds die away above and below.

FIG. 205. — Model of recumbent fold, after denudation.

(*b*) In *similar folds* the beds are thinner on the limbs, thicker in the crests, and the angles between the limbs of successive strata are equal.

(3) The third mode of classification has two types, *open* and *closed,* to which a third, *squeezed,* is sometimes added.

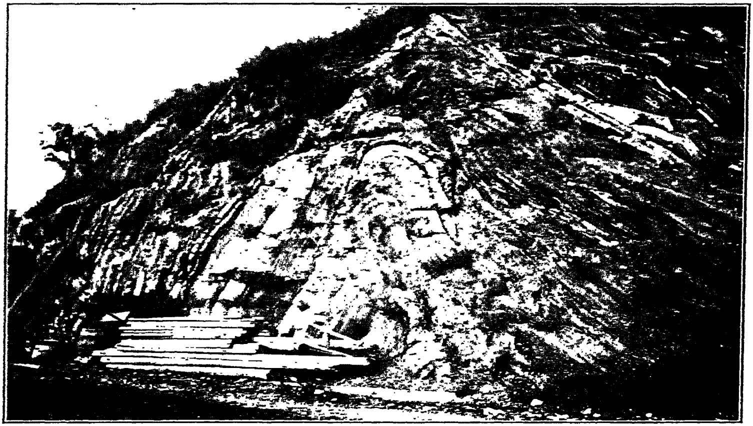

FIG. 206. — Symmetrical, closed anticline, Levis, Quebec. (Photograph by C. D. Walcott)

FIG. 207. — Overturned syncline, Frederick Sound, Alaska. (Photograph by Buddington, U. S. G. S.)

(*a*) *Open Folds* are those in which the limbs of a given stratum are widely separated, and when open folds are gentle and regular, they are said to be *undulating*.

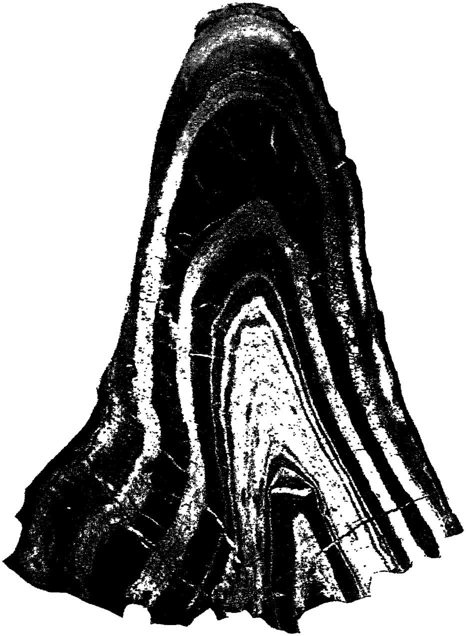

FIG. 208. — Small closed anticline, nearly natural size, showing flow of beds, which are thicker on the crest, Woman River district, Ontario. (Photograph by J. R. Sandidge)

(*b*) *Closed Folds* are those in which the limbs are in contact and any further compression must be relieved by flow and thinning of the beds, or, as Professor Willis has it, "a closed fold is one which cannot bend closer without distorting the bedding."

(*c*) *Squeezed Folds* are those in which "the compression has gone so far as to alter materially the thickness and form of the strata or to shear them off."

Contorted strata are compressed into closed folds, which are connected by sharp, angular turns rather than curves, and *Plications* are intense crumpling and corrugations of the strata. The terms *closed*, *squeezed*, *contorted*, and *plicated* folds represent degrees in the intensity of horizontal compression and when a rock is called *mashed*, the limit is reached, for the rock is shattered to pieces, though it may be subsequently healed by the deposition of cementing material in the interstices. The term *mashed* is not confined, as the others are, to strata, but may be used in connection with any sort of rock.

Isoclinal Folds are of the closed kind and have been so bent back upon themselves that the limbs are all parallel and in close contact. When a series of isoclines has been truncated by erosion, the strata show a continuous uniform dip and appear deceptively like a simple succession of tilted beds, but the frequent repetition of strata of the same material, the same thickness, and in the same order would be good reason for suspecting that appearances were not to be trusted.

Fig. 209. — Isoclinal overfolding, the Blackwater, Ross, Scotland. (Geol. Surv. Gt. Brit.)

Fan Folds have the anticlines broader at the summit than at the base and the synclines broadest at the bottom, a reversal of the normal proportions.

The two classifications, one according to the attitude of the folds, whether symmetrical or asymmetrical, and the other according to the degree of compression to which they have been subjected, are not at all exclusive of each other, but may be employed together. Upright, symmetrical folds may be open, closed, or squeezed, isoclinal, or fan-shaped; oblique and overturned folds

may be in similar combinations, but recumbent ones are necessarily closed. In many forms of closed folds the compression has been so intense that the rocks have been forced to flow, thickening one part of the bed, thinning another, and forming isolated masses which are cut off from their original connections. In Fig. 208 is shown a very small anticline, but little less than natural size, in which some of the layers have flowed, becoming thicker on the crest and thinner on the flanks of the fold.

Everything goes to show that folding is due to horizontal compression, the intensity of which is registered in the character of the fold. Another kind of displacement which is usually called a fold, the monoclinal, owes its shape to vertical, not horizontal, movements of the earth's crust and should therefore be called by the non-committal name of flexure rather than fold.

The *Monocline* cannot be regarded as an exceptional form of the anticline. As its name implies, a monocline has but a single limb, a sharp bend that connects strata lying at different levels. These strata are usually horizontal and otherwise undisturbed, though they may be tilted, but rarely, if ever folded, for the supposed cases of connection of a monocline with folds of the ordinary type, as at the Delaware Water Gap, are very problematical. When traced along the strike, a monocline is very apt to pass into a fault, to which, indeed, it is more nearly akin than to a typical fold. An area of land is slowly raised or depressed, while the adjoining one remains stationary or moves in the opposite sense. The strata yield to this movement by bending, and when the tension becomes irresistible, they break and a fault results. Monoclines are very common in many parts of the West, especially in the high plateau region of Utah and Arizona, where they were first observed and named.

Folding, properly so called, takes place at considerable depths, when the pressure of overlying rock masses prevents fracturing and shattering. Many folds, when carefully examined, exhibit a real flow of material and others a gliding of mineral grains and particles over one another that amounts to plasticity. Many anticlines show a thinning of the limbs when pressure is greatest, and a thickening along the crests when there is some slight relief of pressure. Near the surface of the ground small folds, or what appear to be such, are formed by transfer and readjustment of overlying load, though in such pseudofolds (as they might be called, were that not so barbarous a word) there can be no question of flow or plasticity.

When the Chicago drainage canal was cut through solid limestone, it was given vertical sides and the spoil was dumped along the banks. Removing the load in the channel and increasing it on the sides caused the bottom of the cut to arch upward. The same thing happened in the great Gaillard Cut of the Panama Canal, which, with the slides, deferred the opening of navigation

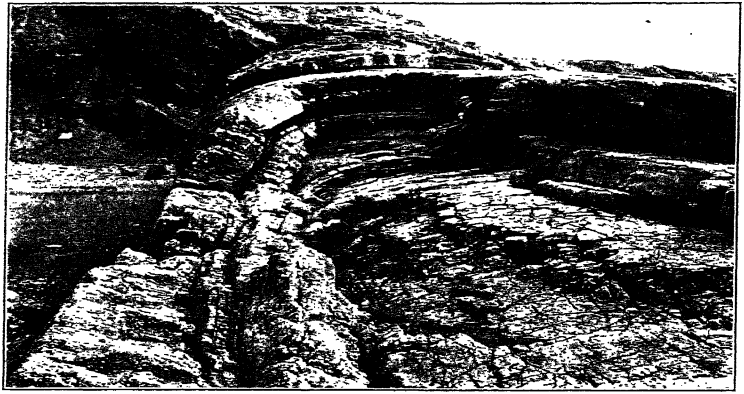

FIG. 210. — Monoclinal flexure north of Broad Haven, Pembroke, Wales. (Geol. Surv. Gt. Brit.)

for a year. In the limestone bed of the Fox River, Wisconsin, the strata suddenly arched upward into a low anticline, bending the steel columns of a mill that stood on the spot. In all of these cases of surface folding and many more that might be cited, the anticlines — for synclines are not formed in that way — are due to the readjustment of joint blocks, not to plastic flow.

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CHAPTER XIX

FAULTS AND THRUSTS

The rocks are often unable to accommodate themselves by bending or by plastic flow to the stresses to which they are subjected, and therefore yield by fracturing, usually accompanied by dislocation, or, in other words, by *faulting*, especially at and near the surface of the earth. This kind of displacement was repeatedly encountered in the study of modern earthquakes (Chap. IX) and older rocks show them in countless thousands. Rocks have no great tensile strength, and no arch of strata 500 feet thick could support its own weight. Hence the universal association of diastrophic movements with fractures which traverse rocks of all geological dates. Any kind of rock may be faulted, but attention must be principally devoted to the stratified rocks, on account of the extreme difficulty of detecting dislocations in thick igneous masses, because of the homogeneity of such masses.

A simple fracture, not accompanied by a dislocation, is called a *fissure;* the strata on the two sides of the crack are the same at corresponding levels, showing that the fissure was made through continuous beds. When the strata on one side of a fracture are shifted in any direction with reference to those on the other side, the structure is called a *fault*. It is generally impossible to decide the actual direction of movement, because so many different directions may give the same result. To take the simplest case, that of a normal fault in horizontal strata (Fig. 211): the appearance produced is that on one side the rocks have been raised (upthrow side) and on the other side depressed (downthrow side), and, no doubt, that is very often just what took place, but not necessarily always. The upthrow side may have gone up or the downthrow side gone down, while the other side was stationary; or both sides may have gone up or down, one more than the other. The example of modern faults is sufficient to show that the movement may have been in any direction, vertical, horizontal, oblique, or

rotational; the one essential feature is that it be different in direction or amount for the two sides.

Movement may be often renewed along the same planes of fracture and in this way displacements of many thousands of feet may accumulate. So far as may be judged from present-day activities, movements on fault planes on the land are limited to a few tens of feet at one time; 75 feet in Iceland and 47 feet in Alaska are the maxima so far recorded, but very much greater ones have registered in the bed of the sea. There is evidence that displacements have gone on intermittently along the same fractures for very long periods of time.

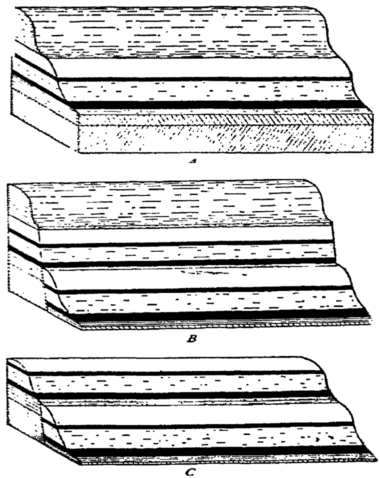

FIG. 211. — Model by Sopwith showing effect of fault on outcrop of horizontal beds. *A*, before faulting; *B*, after faulting, with scarp standing; *C*, scarp worn away.

The economic importance of faults is so great and their bearing upon the problems of mining so vital, that much was learned of them empirically and the early geologists in England adopted the results which the miners had attained, even their terminology. This is still in use, very largely, but many new terms have been devised, especially in this country, where there is great diversity among various writers as to the meaning to be attached to several of the terms. It is therefore desirable to follow the recommendations of a committee of the Geological Society of America on the Nomenclature of Faults. The committee consisted of Professors H. F. Reid, W. M. Davis, A. C. Lawson, and F. L. Ransome, and the report was published in 1913. It was the object of the committee to "make no changes in words which have a recognized meaning" and to "follow the best usage when a word is used in different senses."

Faults may be zones of shattering, or clean-cut fractures, a difference which is largely due to the depth at which the faulting took place, shattering effects occurring near the earth's surface, as a rule. The analysis of a simple type of fault is given in Fig. 212; it is a "normal, strike fault" cutting through inclined strata, the inclination of which is in a direction opposite to that of the fault. Faults may be vertical, but are much more generally inclined, and an important distinction is between high-angled faults which tend toward the vertical and low-angled faults which tend to be horizontal.

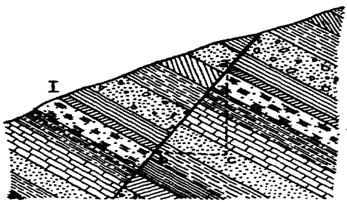

FIG. 212. — Normal strike fault, hading against dip of beds. *I*, downthrow side; *I'*, upthrow; *ac*, throw; *bc*, heave; *ab*, stratigraphic throw; *bac*, angle of hade.

In an inclined fault the angle of inclination measured from a vertical plane is called the *hade*, or *slope* of the fault; measured from a horizontal plane is called the *dip*. Hade and dip are thus complementary and together always equal 90°. In a vertical fault hade = 0, dip = 90°; in a horizontal fault dip = 0, hade = 90°. The word hade is also used as a verb, just as slope is, and a fault is said to hade toward one or the other side in the direction of its dip. The strike of a fault is its line of prolongation. The side on which the beds lie at a higher level than their continuations on the opposite side of the fault, or in other words, the side which has been relatively raised, is called the *upthrow* and the side which has been relatively depressed, is called the *downthrow*, though, as stated above, this may not have been the actual direction of movement. Owing to the inclination of the fault, the beds on one side of the fault project over those on the other and, hence, are the *hanging wall*, and the side which projects beneath the other is the *foot wall*. Either the foot wall or the hanging wall may be on the upthrow, or the downthrow side, according to the nature of the fault.

Two kinds of local movements on faults are recognized: (1) "*Translatory movements* are those in which all straight lines on opposite sides of the fault and outside of the dislocated zone which were parallel before the displacement are parallel afterward. . . . (2) *Rotatory movements* are those where one side of the part

of the fault under consideration has suffered a rotation relative to the other side.

"No faults of any magnitude exhibit merely translatory movements over their whole lengths. Faults die out and the displacement is not uniform along them, so that there is necessarily some slight rotation." The vertical displacement between the two severed ends of a given bed as measured in a mine shaft, for instance, is called the *throw* (Fig. 212 *ac*, Fig. 213 *AC*). Owing to the obliquity of the fault, the severed ends are separated horizontally as well as vertically, and this separation is called the *heave*, or *horizontal throw* (Fig. 212 *cb*; Fig. 213).

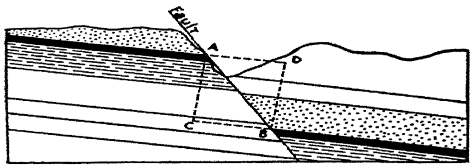

FIG. 213. — Normal strike fault hading with dip of beds. *AC*, throw; *BC*, heave; *DB*, stratigraphic throw.

FIG. 214. — Fault breccia of limestone.

The heave is due to the obliquity of the fault and therefore increases, relatively to the throw, as the hade increases; a vertical fault having no hade can have no heave. *Offset* is the distance between the two corresponding ends of a faulted bed

measured on a horizontal plane and usually applied to the outcrop (Fig. 224, III). The committee suggested two new terms for the measurement of fault displacements: "*Slip*, which indicates the relative displacement of *formerly adjacent points* on opposite sides of the fault, *measured in the fault surface*. *Shift*, which indicates the relative displacement of *regions* on opposite sides of the fault and *outside the dislocated zone*." (Rept. of Committee.)

FIG. 215. — Vertical slickensides on hanging wall of fault; footwall eroded away, Rondout, N. Y. (N. Y. State Geol. Surv.)

In the shattered zone the innumerable fragments of rock are often cemented together into a *fault breccia* by the deposition of some mineral, usually calcite, from solution in percolating waters. In soft rocks the fault is always closed by the immense pressures involved, but in rigid rocks it may remain partly open, if the fault surface be warped or irregular, as is generally the case. The term *fault plane* is thus rarely accurate, though it is employed as a matter of convenience. In faults of considerable throw, where presumably movement has been frequently repeated, the ends of the adjacent strata are sharply bent upward, or downward, according to the direction of the movement; this is *drag*. In the harder rocks the grinding of upthrow and downthrow sides polishes and grooves the fault surface in the characteristic way known as *slickensides*. The grooves or striæ indicate the direction of the *last* movement, which usually obliterates those of preceding movements, but sometimes a patch of older slickensides is not impinged upon in the renewed movement. Thus, some specimens have preserved two or even three sets of striæ, each set recording the movement in a different direction.

Primarily, faults are classified according to their relation to the attitude of the strata. (1) *Strike faults* are those which have a course parallel to the strike of the beds. Most of the major faults of great elongation are strike or *longitudinal* faults, so called because, like longitudinal valleys, they are parallel to the axes of folds, and the "grain of the country generally."

(2) *Dip Faults* are parallel to the dip of the strata and therefore at right angles to the strike faults. They are usually of no great length and are also called transverse, because they cut across the grain.

FIG. 216. — Drag of strata at fault, near Dalhousie, New Brunswick.

(3) *Oblique Faults* are oblique to the strike of the strata and intermediate between dip and strike faults.

A fourth kind, *bedding faults*, are thus defined in the Committee's report. "*A bedding fault* is a special form of strike fault whose surface is parallel with the bedding of the stratified rocks." Figure 217 shows so-called bedding faults, which are along the dip of the beds, not the strike, and it is manifestly improper to call them faults, for there is no fracture involved. Some of the strata have been pushed up along the bedding planes higher than others and the structure is of very minor importance. The first effect of faulting of any description is for the upthrow side to form a line of cliffs or bluffs called the *fault scarp*, which, under favoring conditions,

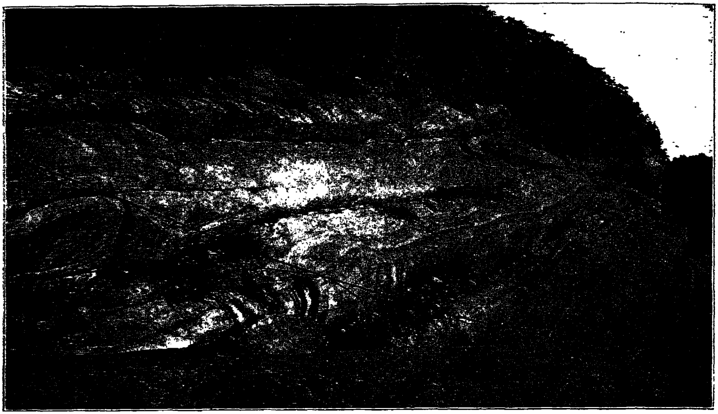

Fig. 217. — Limestone faulted on bedding-planes, with vertical slickensides, Rondout, N. Y. (Photograph by van Ingen)

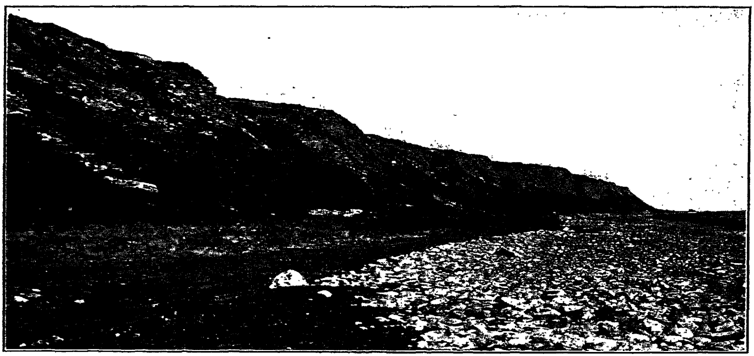

Fig. 218. — Fault scarp of great Glen Fault, near Hilton of Cadboll, Ross, Scotland. (Geol. Surv. Gt. Brit.)

may long persist. In the great majority of cases, however, the scarp is removed by denudation, so that both sides are on the same level or on the same continuous slope, with no surface feature to indicate the dislocation, which must be detected by indirect evidence.

Another method of classification is in accordance with the nature of the relative movement on the two sides, as the actual movement can seldom be determined.

Fig. 219. — Small, nearly vertical fault, showing drag, Little River Gap, Tenn. (Photograph by Keith, U. S. G. S.)

A. High-Angled Faults

I. Vertical Faults

1. *Normal Faults* (also called gravity faults) are those in which the fault hades toward the downthrow side, which therefore forms the hanging wall, while the upthrow side is the foot wall. The term *gravity fault* is used because of the appearance of the down-

throw side's having simply slipped down the fault plane under the influence of gravity. Sometimes, no doubt, it did so, but, as was pointed out before, all that can be confidently stated is that there was a differential movement of the two sides.

Strike Faults belong in the normal and reversed categories, but may be mentioned here. Normal faults are not always strike

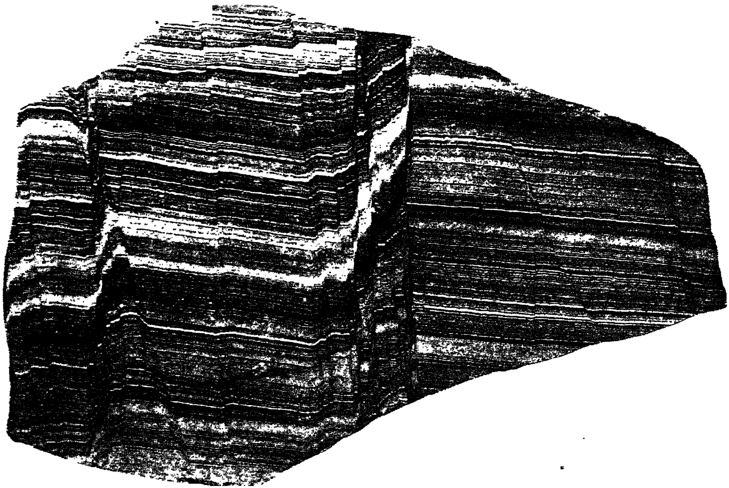

FIG. 220. — Slab of fault-rock, Buffalo Gap, S. D., about one-half natural size. (Photograph by J. R. Sandidge)

faults, for they occur also in horizontal beds which have no dip or strike. A *compound fault* is made up of a number of parallel dislocations, which unite, or branch ; they may hade in the same or in opposite directions, but, in the latter case, one hade prevails over the other. A series of parallel faults, all hading in the same direction, are called *step faults*, because they form a gigantic staircase, so long as the scarps remain standing. If two parallel fault planes hade toward each other so as to intersect below, they form a *trough*, or, better, a *trench fault*, and include a wedge-shaped block, which

is on the downthrow side of both displacements. If they hade away from each other, the included block is on the upthrow side of both faults and is called by the German word *Horst*, for there is no English term. There is a tendency among English-speaking geologists to use the term *Graben* for a trough fault, but this is unnecessary, as *trench* is an exact equivalent. On a very large scale trenches are called *rifts, rift valleys,* such as are found in such astonishing magnitude in East Africa.

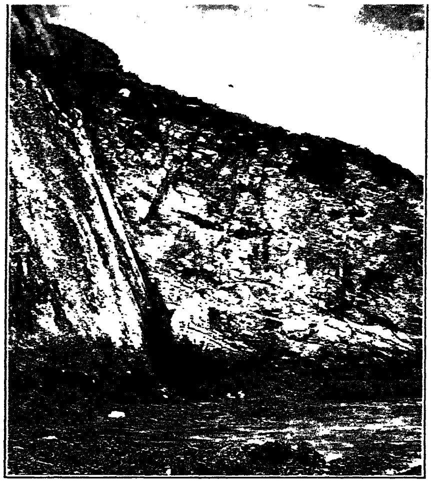

Fig. 221. — Normal, high-angle fault, Port Namarch, Wales. (Geol. Surv. Gt. Brit.)

However long it may be, a fault sooner or later dies away, by diminution of the throw, until it vanishes. This implies that the strata are very gently arched along the plane of dislocation, upward on the upthrow side, downward on the downthrow. That this curvature is not distinct to the eye is for the same reason that the earth appears to be flat, so little of it can be seen in any one view.

Faults, in most cases, produce very great effects upon the outcrop of the strata involved, effects which are sometimes very deceptive after denudation has planed down the scarps, and when beds of economic value are concerned, failure to detect faults may lead to serious loss. The manner in which outcrop is affected is determined by the direction and throw of the fault and by the attitude and dip of the beds. Strike faults of moderate throw that traverse horizontal beds, or beds dipping in a direction opposite to the hade of the fault, repeat the outcrop of the beds, as shown in Figs. 211 and 222. When dislocated by a series of step faults, a given stratum has a number of outcrops greater by one than the

number of faults. In Fig. 222, for example, which is a model of an actual area in the English coal measures, a surveyor might easily be misled into believing that seven seams of coal were cropping out on the hills and in the shallow valley between them, whereas, in reality, there are only two such seams, with outcrops repeated by faulting. When a strike fault hades in the same direction as the dip of the strata, a certain number of the beds abut against the fault plane and fail to reach the surface, as may be seen from Fig. 213. In great faults with displacements of many thousands of feet, the beds cropping out on the two sides of the fault are

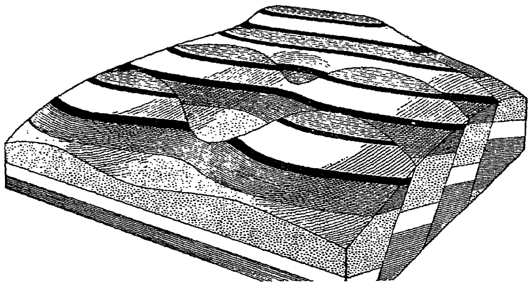

FIG. 222. — Effect of step faults in repeating outcrops. (Model by Sopwith)

entirely different. The deep-seated strata exposed by denudation on the upthrow side are carried so far down on the downthrow that they do not reach the surface at all, or only at a distance from the fault.

2. *Reversed Faults.* This group is often so defined as to include low-angled faults, or thrusts, but as employed here embraces only those high-angled faults in which the hanging wall has been pushed up over the foot wall and therefore forms the upthrow side, toward which the fault plane hades. Reversed faults, which are almost always parallel to the strike, are crowded together and occupy less space, when measured across the fault plane, than they did before dislocation. In a large faulted area, normal and reversed faults frequently occur together, tension in one place compensating compression in another, and the two kinds of dislocations appear to have been formed at the same time or in close succession.

The names normal and reversed were first used in England, where the former class happened to predominate, but if any one could complete the colossal task of enumerating the faults throughout the world, it is a question as to which class would be found to have the more numerous examples.

Dip Faults are, in general, parallel to the dip of the beds and therefore cross or branch out from the strike faults of a region, more or less at right angles, being generally shorter and of smaller throw.

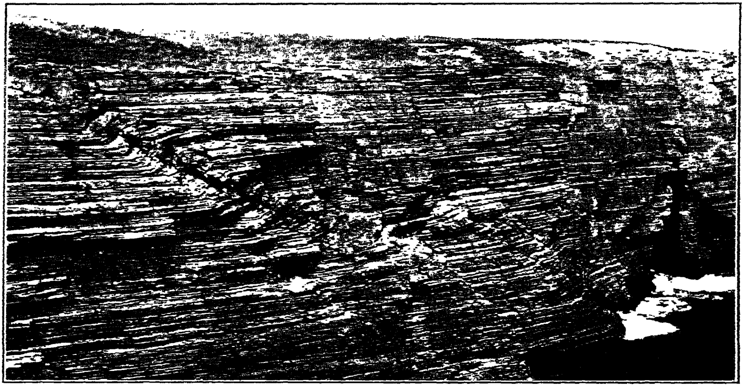

Fig. 223. — Small reversed fault, Caithness, Scotland. (Geol. Surv. Gt. Brit.)

Dip faults cut across the strike of the beds and interrupt the continuity by producing an offset in the outcrop of a given stratum, which ceases abruptly at the line of fault and, when found on the other side, is seen to be shifted for some distance along that line. How such horizontal shifting is brought about by a vertical movement is shown by the model, Fig. 224. In I is seen the model before faulting, the black band representing a dipping bed. In II the block has been faulted, the upthrow side standing as a fault scarp, while III shows the scarp removed by denudation. On the downthrow side the outcrop is shifted in a direction opposite to that of the dip of the beds and, on the upthrow side, in the same direction as the dip.

When a dip fault cuts across eroded folds, the distance between the two outcrops of the same stratum in the two limbs of an anticline is increased on the upthrow side, diminished on the downthrow; in the synclines this effect is, of course, reversed. The effect is due to the fact that, when both sides are planed down to the same level, the surface of the ground cuts through the beds at a lower *stratigraphic* level on the upthrow than on the downthrow side and, as the limbs of an anticline diverge downward, the outcrops will be the more widely separated the lower the level at which they reach the surface. The limbs of a syncline converge downward and the effect of a dip fault upon the outcrops is the reverse of what it is in the anticline.

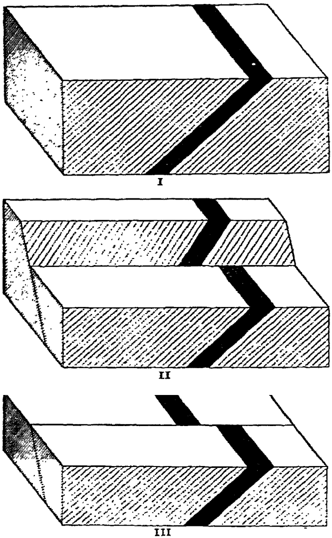

FIG. 224. — Model showing offset of outcropping bed by a dip fault. I, before faulting; II, fault scarp standing; III, scarp removed.

Oblique Faults. Dip faults do not always exactly follow the dip of the beds and strike faults often deviate considerably from the strike, and sometimes the fault is neither one nor the other, but midway between the two, and is then called an oblique fault. The outcrop of a given bed, obliquely faulted, has an offset, as in the case of a dip fault, but if the oblique fault hades with the dip of the beds, there is a gap between the two adjacent ends of the outcrop, the gap widening as the line of the fault approaches the line of strike. If the fault hades in the opposite direction from the dip, the two ends of the outcrop overlap.

II. Horizontal Faults (or Heave Faults)

In displacements of this class the principal direction of movement is horizontal and in horizontal strata may easily escape detec-

tion. When the strata are inclined, a horizontal displacement produces effects which, in cross section, cannot be distinguished from those of ordinary normal and reversed faults, except when the striæ of slickensides remain to indicate the actual direction of movement. The deceptive appearance is the exact counterpart of that produced by a dip fault, in which a vertical movement seems to

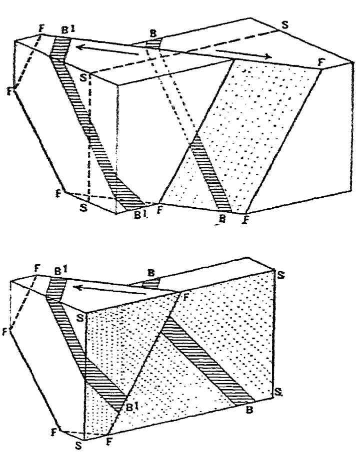

FIG. 225. — Model illustrating horizontal faulting, with hanging wall moved against dip of beds. Upper figure (modified from Ransome), block after dislocation. Lower figure, cross-section on plane SSSS; BB, B′B′, stratum of reference. FFFF, faultplane.

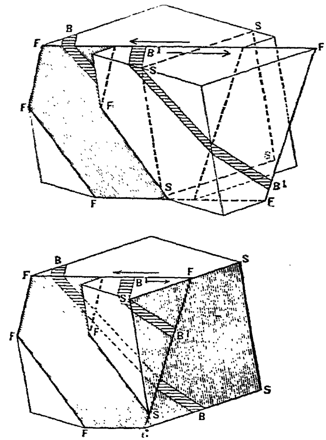

FIG. 226. — Model illustrating horizontal faulting, with hanging wall moved with dip. Upper figure (modified from Ransome), block after dislocation. Lower figure, cross-section on plane SSSS. Lettering as in Fig. 225.

cause a horizontal offsetting of the outcrop. This is illustrated by the models, Figs. 225 and 226, which shows that if the hanging wall is moved horizontally in a direction opposite to that of the dip of the strata, an apparently normal fault will result, while if it is moved in the direction of the dip, a seemingly reversed fault will be produced. Horizontal faults do not form scarps, for there is no

vertical movement, but in certain cases there is a movement obliquely upward, as is shown by the slickensides. What would ordinarily be regarded as typical normal and reversed faults may be produced by the same movement. Heave faults were supposed to be rare, but are now known to be quite common; the amount of dislocation in them is limited, as compared with the vertical faults, which allow any degree of upward movement, but when

FIG. 227. — Horizontal slickensides, Okla. (U. S. G. S.)

the mosaic of fault blocks, large and small, in nearly any mining district, is studied, it becomes obvious that almost any possible direction of movement will assuredly be manifested by some of the blocks.

III. Rotatory Faults

In any prolonged fault there is apt to be more or less rotation, because of unequal friction and resistance of the walls. In certain instances the movement of rotation is the principal one, exceeding any movement of translation. The result is that the hanging wall drops on one side of the axis of rotation, producing a normal fault, and on the other side it rises, forming a reversed fault, the effect of a single movement.

Systems of faults of different geological dates frequently traverse the same region, intersecting one another at all angles. An older fault, crossed by a newer one, is itself faulted and offset. The intersecting faults divide the strata into large and small *fault blocks*, which are generally tilted in different directions, but, as a rule, the beds are not strongly folded. Though faults occur in regions of horizontal strata, there is, nevertheless, frequently a close connection between faults and folds, folds often passing into faults, the strata bending in one part of their course, fracturing in another.

B. Low-Angled Faults — Thrusts

A thrust is like a reversed fault in that the hade is toward the upthrow side, which is the hanging wall, and several writers include them in the category of reversed faults. It seems better, however, to make a separate major division for them because of the different manner of their production and their association with violent compression and folding. The surface of dislocation in thrusts tends to assume a horizontal position and hence the term of "low-angled faults." This is not invariably a suitable designation, for sometimes thrusts have quite steep inclinations, as in the Rocky Mountain region of Canada and the United States. In the Front Range of the Rocky Mountains there is a great deal of thrusting, the overlying masses having been carried eastward from 7 to 10 miles. The northwestern Highlands of Scotland exhibit thrusting on a gigantic scale, quite dwarfing the puny movements in the Rockies. For nearly a century the structure of the Highlands completely baffled geologists until the solution of the enigma was found by Messrs. B. N. Peach and John Horne. In one of the Memoirs of the Geological Survey of Great Britain (1907) the labors of many years were summed up. Mr. Horne writes: "By lateral compression of the earth's crust the rocks have been thrown into a series of folds, usually inverted, accompanied by several faults or thrusts. . . . In the middle limb of the over-fold the constituent particles are attenuated, and along that limb, the over-fold may or may not pass into a reversed fault.

"Without incipient folding the strata are repeated by a series of minor thrusts or reversed faults, which lie at an oblique angle to more important dislocations termed by us major thrust planes.

"Thrusts of smaller magnitude, when followed along the strike,

may merge into folds." In the Highlands rock masses have been carried bodily more than fifty miles over the unyielding "sole" of the thrust plane. The minor thrusts, parallel to one another and oblique to the major thrust plane, make the structure called *imbricated*, which is due to friction between the moving masses along the sole, as the upward facing surface of the thrust plane is called.

Thrusts are also common in the Appalachian Mountains, where they are generally caused by the breaking of folds, which are sheared by compression. The irregular occurrence of folds and

FIG. 228. — Small, local thrust, Juniata River, Penn. (Geol. Surv., Penn.)

thrusts in Pennsylvania, Virginia, and Tennessee "was subsequently explained as a result of the difference of load resting on more or less deeply buried strata. In each section the controlling stratum was a very thick limestone, which under less load broke and was overthrust at an earlier stage of development of the folding than where it was more heavily loaded." (Willis.)

Thrusts of small magnitude are frequently produced near the surface, where the overburden is moderate (Fig. 228).

Two classes of thrusts, *overthrusts* and *underthrusts*, are recognized. An overthrust is produced when a mass of strata is pushed up over an unyielding, underlying mass, and the surface along which the translation is effected is called the *sole*. An overthrust may be made up of several minor fractures steeply inclined to the

sole, the structure which has been called *imbricated* and which is due to the retardation and breaking through friction. If thrusting occurs near the surface of the earth, imbrication is, theoretically at least, inevitable, but may not occur if it is deep-seated. In underthrusts the moving mass is pushed beneath a stationary block and the outcome is the same, except that if the bottom of the translated block is exposed, there must be a second sole below and the underthrust mass must be a wedge.

FIG. 229. — Thrust, Carmel Head, Anglesey, Wales. (Geol. Surv. Gt. Brit.)

C. The Causes of Folding and Dislocation

Like all operations which take place deep within the earth, the causes of crustal deformation are incapable of direct observation and are very obscure. There is therefore much difference of opinion regarding these processes, for the view which is held concerning the physical state of the earth's interior will necessarily determine possible hypotheses as to the genesis of folds, faults, and thrusts.

The first step must be to ascertain, if possible, the direction in which the folding and dislocating forces acted. It might seem obvious, on a superficial examination, that the direction was ver-

FIG. 230. — Jurassic limestones overthrust 8 times and repeated 9 times in 11 miles, Andes of northern Chile. (Gift of Prof. B. Willis)

tically upward, with maximum pressure beneath the anticlines and minimum beneath the synclines. But such an explanation could, at most, apply only to the upright, symmetrical, and open folds and is not really satisfactory even for such cases. Pressure acting upward would stretch the beds in the anticlines, for folded strata, measured across the axes of the folds, occupy less space than before, unless they have been stretched like sheets of rubber. In most instances the beds are thicker in the folded portion of their course than in the undisturbed area of the same beds. Sometimes, it is true, beds are thinned in the limbs of the anticlines, but then it is obviously caused by squeezing and flow, not to tension. Such an explanation is entirely inadequate to account for closed, inclined, and inverted folds, to say nothing of contortion and plication, or for compound folds one within the other. Microscopic examination of folded rocks shows clear evidence of compression and the more intense compression as the folding is closer.

If the folding force did not act vertically, it must have done so horizontally, tangentially to the curvature of the earth, a fact which is now almost universally conceded. A horizontal force would compress and crumple the beds, producing different types of folds according to conditions, such as depth of burial, which determines the amount of overload. The same bed which, near the surface, will shatter under compression, will bend, when sufficiently loaded. Different rocks behave very differently under the same compression; shales will fold when accompanying rigid limestones are, seemingly, quite unaffected. Thrusts, like folds, are due to compression, for the space occupied by the beds is reduced from the condition before dislocation. Both folded areas and those contracted by thrusting are subject to vertical upheaval, as will be more particularly seen in the chapter on mountain ranges; this upward movement may take place during or after compression.

The direction of movement in high-angled faulting and the manner in which the force acted upon the fault blocks are much less obvious than in folding or thrusting. Across the fault plane, normally faulted beds occupy more space, by the amount of the heave or horizontal throw. From this it has been generally inferred that normal faulting is due to tension and reversed faulting to compression. This may have been true in many localities, but it is usually impossible to say with confidence just what the

direction of movement of fault blocks has been. In a normal fault the downthrow side seems to have slid down the inclined plane of the fault surface, but the same appearance would be given had both sides been raised by compression, the upthrow more than the other, which would give the necessary additional space demanded by the heave.

In some instances normal faults have been generated by compression acting from the ends of the faulting, arching the upthrow side upward and the downthrow downward, thus producing tension at right angles to the line of compression. Faults of this description have been observed in central Pennsylvania, Tennessee, and Alabama.

That horizontally acting forces are the causes of compression is generally accepted and that vertical movements may also be due to compression is probable in certain instances.

The formation of trenches and rift valleys illustrates the different interpretations put upon undisputed facts. One explanation of the west Rift Valley in Africa is that the immense crack was torn open by tension and the wedge-shaped block which forms the bottom of the valley was dropped down between the two upthrow sides. If the latter remained relatively stationary, the wedge must have been forced into a narrower space and therefore its strata would be folded, a point which has not been determined for the dropped downthrow block of the Rift Valley. This hypothesis of tension is the one which has been maintained by Professor J. W. Gregory, of Glasgow, while Mr. E. J. Wayland, Director of the Geological Survey of Uganda, is of a different opinion, for he "could not thus account for the high plateaus between which Lake Albert lies, nor for the elevation of Mount Ruwenzori, a mountain block which is part of the same zone. The plateaus and Ruwenzori have been forced up. The block under Lake Albert, he reasoned, has been forced down. The whole great structure is a result of horizontal compression acting on wedge-shaped masses. The upper ones have risen on inclined planes."

That many direct upheavals are not to be accounted for by compression is also exceedingly probable. How these horizontal stresses of compression and shearing are generated is an unsolved problem. Some geologists continue to accept the hypothesis of secular contraction of the earth from cooling, though others reject

it altogether. The contraction hypothesis can best be considered in connection with the study of mountain ranges and will be taken up in Chapter XXI. Here it is merely mentioned for the sake of completeness.

An entirely different type of explanation seeks to account for the phenomena of faulting by the transfer of molten magmas within the earth. In certain regions, as in the Tonopah mining district of Nevada, it has been made very probable that such transfers are the actual cause of the fracturing and dislocation of strata and some observers would give to this principle a general application. Proof is lacking, however, that more than a local importance is to be attributed to this process.

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CHAPTER XX

JOINTS — UNCONFORMITY

It has been repeatedly stated that all rocks within the reach of observation, except loose and incoherent bodies, such as sand and gravel, are divided into blocks of greater or less size by systems of cracks and crevices, which are called *joints*. Attention has been called to the important part which joints play in all the processes of denudation, in the circulation of ground water, and in determining the lines of drainage and other topographic features on the earth's surface. It remains to consider them from the point of view of causation. Much has been learned regarding this difficult problem, but much remains that is still obscure. Though having certain factors in common, the joints of igneous rocks are produced quite differently from those of sedimentary rocks. In the former class all joints are truly so called, but in stratified rocks the bedding planes act as one of the three sets of joints which bound each block. In igneous rocks, joints are shrinkage cracks, caused by the contraction of the mass as it cools after solidification. As the tensile strength of the mass is insufficient to overcome its great weight, it must crack as it shrinks and it must shrink as it cools. The joints vary greatly in different rocks and for the same kind of rock in different localities, both in their number and their angles of intersection, producing corresponding variety in the size and shape of the joint blocks.

In very fine-grained and homogeneous rocks of the igneous class there is a general tendency to columnar jointing which is especially characteristic of basaltic lavas, though by no means confined to them. All over the world, in basaltic lavas, in modern flows and sheets, as well as in very ancient ones, the wonderfully regular, hexagonal column recurs. So regular are these joint blocks, that it seems quite incredible that they are really natural, not artificial products. Joints form at first as cracks in the surface of the heated mass and extend down into it as cooling proceeds,

so that the long axis of the columns is at right angles to the cooling surface, or surfaces. The cracks follow lines of least resistance, thus accounting for their regularity in homogeneous rocks, in which the hexagonal columns are so frequent. There are only three regular figures which will cover the whole of a plane surface and these are squares, hexagons, and equilateral triangles; the square requires for its formation the intersection of systems of four cracks radiating from equally spaced points; equilateral triangles must have systems of six cracks, while hexagons are

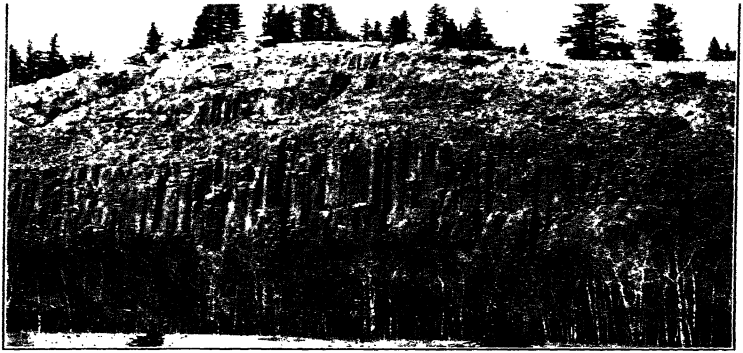

FIG. 231. — Hexagonal joint columns in basalt, Australia Creek, British Columbia. (Geol. Surv., Canada)

formed by sets of three cracks radiating at angles of 120° from one another. As the hexagons are not mathematically perfect figures, small irregularities are compensated by occasional triangular or pentagonal prisms. As the columns form they contract lengthwise and are broken up into a series of segments by transverse cracks. In the famous Giants' Causeway, on the north coast of Ireland, which the sea has cut down into a platform seemingly paved with hexagonal blocks, the transverse joints are concave, forming shallow balls and sockets, astonishingly artificial in appearance. Owing to the method of formation, the cracks working inward from the cooling surfaces, the columns are vertical in sheets, sills, and lava streams, horizontal in dykes. In irregular bodies,

the columns are sometimes in radiating groups and sometimes in most curious shapes. On the island of Staffa, so celebrated because of Fingal's Cave, the basaltic columns of Clam Shell Cove accurately form the half of a keel-boat seen in cross section.

As was mentioned above, hexagonal columns, though most frequent in basaltic lavas, do occur in other kinds of rocks, both volcanic and plutonic. The foot of Obsidian Cliff, a flow of glassy,

FIG. 232. — Columnar jointing in trap, Orange, N. J. (Photograph by Darton, U. S. G. S.)

acid rhyolite, displays quite regular columns as also does the wonderful Mato Teepee (or Bear Lodge, Fig. 18) which springs 700 feet into the air. The plutonic mass of phonolite is beautifully jointed and looks like a great cluster of organ pipes. As previously noted, the Palisades of the Hudson owe their name to the rough columns of the cliff which fronts the river. In the columns unearthed in a trap sheet near Orange, New Jersey, and in the very remarkable "Devil's Post Pile," in the Sierra Nevada of California, many of the vertical joints are sinuous, giving transverse flutings. A list of places where hexagonal columns in lava sheets

are to be seen would include almost all countries and islands of the world, so widespread is this mode of jointing in lavas, yet they never fail to excite wonder in the beholder, so surprising is their look of artificiality.

Many of the granites and other coarse-grained igneous rocks are quite regularly jointed into rectangular, more or less cubical blocks, or long prisms, or broad slabs and plates. Monolithic

Fig. 233. — Jointing of granite, cañon of Animas River, Colo. (Photograph by Cross, U. S. G. S.)

columns of granite, forty feet or more in height, like those in the United States Treasury in Washington, are yielded by many quarries; other granites are in slabs, and others again have joint blocks that are extremely irregular in form and size. A peculiar feature, present in many granites, is the system of curved partings, too obscurely marked to be called joints, which are developed by weathering and result in the dome-like masses, which are displayed, on very different scales, at such widely separated places

FIG. 234. — Curved joints in basalt, simulating a syncline, Tippity Green, Rowley Regis, Staffordshire, England. (Geol. Surv. Gt. Brit.)

as the Yosemite Valley, California, and the Matoppos Hills of Rhodesia.

The diabase of the Palisade sill, which has the columnar jointing on the river front, is in other exposures exceedingly irregular in the size and shape of the blocks (Figs. 5 and 6). In the Bergen Cut, by means of which the Pennsylvania Railroad enters Jersey City, there are some very large slabs, with many small and irregular blocks. At Rocky Hill, New Jersey, there is so

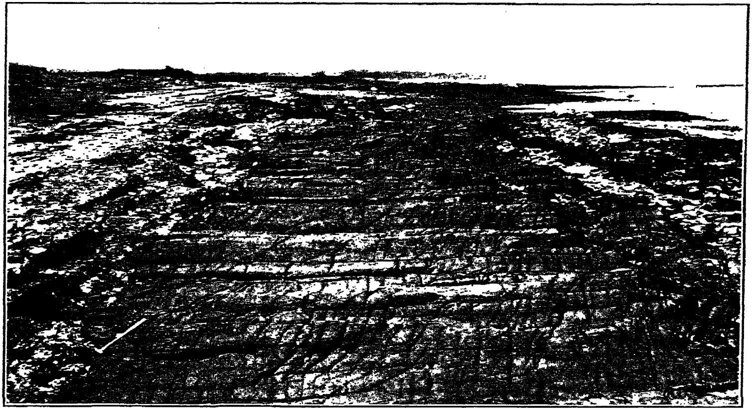

FIG. 235. — Horizontal columns in basalt dyke, Mull, Argyll, Scotland. (Geol. Surv. Gt. Brit.)

marked a tendency to jointing in horizontal plates (Fig. 73) as to produce a deceptive appearance of stratification.

As igneous rock masses are subject to diastrophic movement and are elevated and depressed, faulted and overthrust like other rocks, many joints must be due to such movements, but there is no way of distinguishing them from the shrinkage cracks of cooling.

In sedimentary rocks a certain limited amount of jointing is due to settling and shrinking of drying sediments, of which mud cracks are an instance, but most of the joints of stratified rocks are due to diastrophic movements subsequent to the consolidation of the rocks. Joints are in more or less parallel *sets*, which meet

one another at angles characteristic for the various kinds of rock, but usually do not cross. "Joints are caused by tension or by compression, or by some combination of these stresses, as in torsion, or cross-bending." (Leith.) While this statement is doubtless true, it is exceedingly difficult to assign the jointing of a particular rock to a specific cause. Joints in folded and tilted rocks are apt to be parallel to the strike and dip of the beds and hence are called *strike joints* and *dip joints* respectively; the former are the more important and the more persistent.

FIG. 236. — Master joints in argillite, Princeton, N. J. (Photograph by F. Anderegg)

Master joints, another quarryman's term, are those major partings which pass through several strata and continue for considerable distances, nearly always parallel to the strike of the beds; ordinary joints are as a rule confined to a single bed. Master joints may be regarded as incipient strike faults, in which there has, as yet, been no dislocation. Joints are most conspicuous at and near the surface of the ground, partly because the blocks are freer to separate and partly because the weathering agents constantly tend to widen the cracks. In very firm rocks, deep under ground, the joints may be very obscure, even invisible, when they are called *blind joints*. When a rock traversed by a blind joint is struck with a hammer, it separates into two blocks,

with smooth, plane faces, very different from the rough surfaces of a fracture, showing the reality of even an invisible parting. Although joints diminish downward, no level has yet been reached in which they entirely disappear. It may be inferred, however, that they are absent in the lower parts of the earth's crust.

The art of quarrying stone for all sorts of purposes consists in taking advantage of the system of joints to dislodge the blocks with a minimum of effort. The quarry front is so worked that one set of joints form the *face* and another set the *ends*, which enables the workmen to wedge out the blocks and not cut into the face with pick and chisel as though it were a bank of earth. Blasting, skillfully managed, is so devised as to loosen great masses of joint blocks with as little shattering of the blocks as possible. Of course, when the object is merely to remove the stone, without utilizing it, as in tunnels and excavations, no precautions against shattering need be taken.

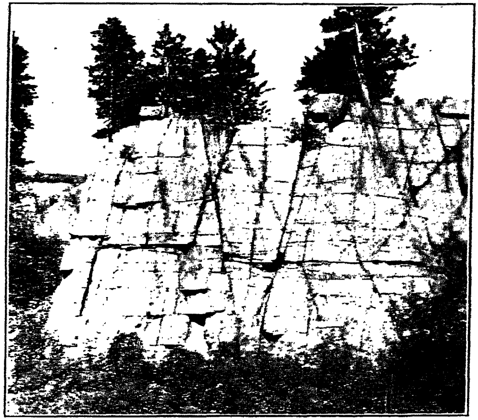

FIG. 237. — Torsion joints in quartzite, Pennington Co., S. D. (Photograph by Johanssen, U. S. G. S.)

1. *Tension Joints.* The convex sides of folds are under tensile stress, and if they are not deeply buried, the stretching may result in a system of cracks which are radial to the curves of the folds and which follow the strike of the beds. Folds are not horizontal longitudinally, but pitch in the direction of their axes, and this complex bending may produce two sets of tensile stresses, perpendicular to each other, and thus cause two sets of joints, one following the strike, the other the dip of the beds. Tension joints produce either rough and irregular, or smooth, clean-cut faces,

as is determined by the character of the rock. In weakly cemented sandstones the joint planes pass between the sand-grains, while in hard, firm, and fine-grained rocks the faces are smooth.

2. *Torsion Joints.* Torsion means twisting, and though torsional stresses may be analyzed into tensile and compressive stresses, the combination is quite different from either component. It is difficult to imagine any diastrophic movement, whether of warping or of simple elevation or depression, which should be so uniform and so evenly supported at all points as not to give rise

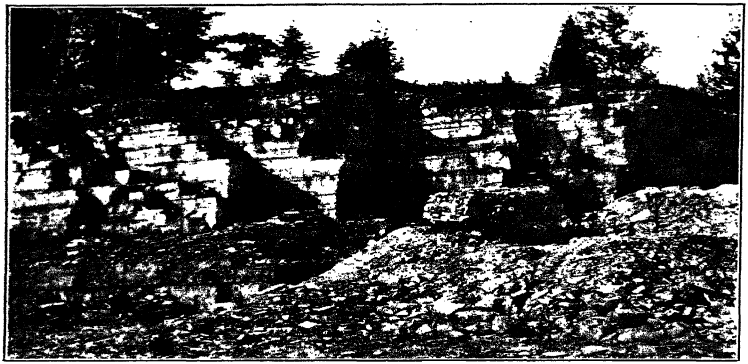

FIG. 238. — Rectangular joints in limestone, Drummond Island, Mich. (Photograph by Russell, U. S. G. S.)

to torsional stresses. Daubrée's famous experiment of twisting a sheet of plate glass shows the result of such stresses upon a brittle substance; the resemblance to systems of joints is obvious. How very slight the movement need be is shown by the prevalence of joints in horizontal, low-lying beds that have undergone very little displacement. Even the modern limestones that form around a coral reef and are still awash in the sea are jointed, following the universal rule.

3. *Compression Joints* are caused when rocks yield along the shearing planes. A shearing stress is produced when a mass is subject to pressure which differs in amount in different directions. If the cause of the stress is simple compression, the shearing planes

form an angle of 45° or more with the direction of the pressure. The shears produced on the limbs of folds are strike joints; dip joints may also be formed, but less regularly. In some conglomerates the joint planes shear through hard quartz pebbles and sandy matrix alike, with a smooth and shining face on the pebble. Tension would assuredly pull the pebble out of its bed but could never tear it in two; only shearing could produce so clean-cut a parting.

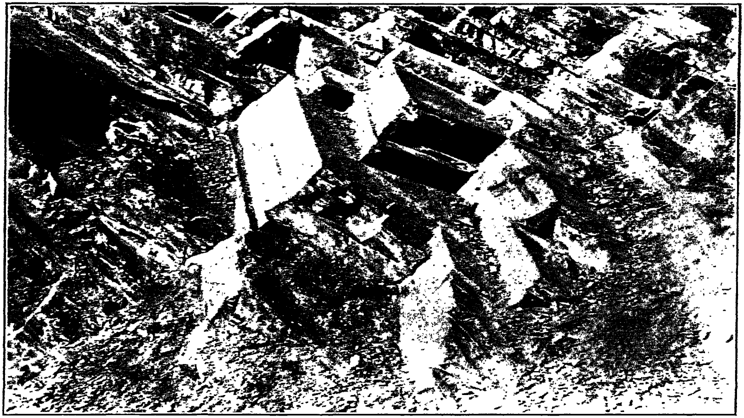

FIG. 239. — Rectangular joints in hard shale, Shoshone Co., Idaho. (Photograph by Calkins, U. S. G. S.)

A. Cleavage and Fissility

Cleavage is the capacity of a mineral, or a rock, to split in certain directions more easily than in others. Mineral cleavage, which has already been considered in connection with the rock-forming minerals (p. 26), is due to the molecular structure of the crystal, while rock cleavage, often called *slaty cleavage*, is caused by the character of mineral particles, visible under the microscope. "Rock cleavage is due to the arrangement of the mineral particles, with their longer diameters, or their readiest cleavage, or both, in

a common direction, and this arrangement is caused: first, and most important, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third, and of least importance, by the rotation into approximately parallel positions of random original particles." (Van Hise.)

The new minerals, to the development of which rock cleavage is so largely due, are few in number and include the micas, chlorite, hornblende, quartz, and the feldspars. Other minerals function

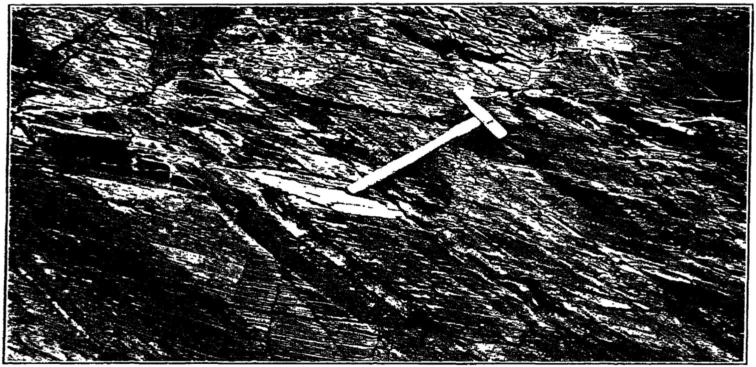

FIG. 240. — Cleavage in slate; foreshore of River Camel, Wadebridge, Cornwall, England. (Geol. Surv. Gt. Brit.)

in similar manner, but very much less frequently. Two sorts of rock cleavage are distinguished: "*Fracture cleavage* is conditioned by the existence of incipient, cemented, or welded parallel fractures, and is independent of a parallel arrangement of the mineral constituents. *Flow cleavage* is conditioned solely by a parallel arrangement of the mineral constituents." (Leith.)

Since Professor Adam Sedgwick, of Cambridge, first described it in 1835, the observation has repeatedly been made that in flow cleavage the cleavage planes in folded rocks run parallel with the axes of the folds, intersecting the lines of stratification at constantly changing angles and maintaining their parallelism to one

another, or in Sedgwick's phrase, "preserving their parallelism in spite of undulations and anticlinal lines."

Ordinary roofing slate is a typical example of flow cleavage, from which the term *slaty cleavage* is derived. When beds of slate are interstratified with beds of coarser material, the cleavage is usually quite perfect in the slate, absent or imperfectly developed in the coarser rocks.

The cause of flow cleavage is undoubtedly compression, for it occurs only in compressed rocks as indicated by the folding, and it is unknown in horizontal strata. The microscopic structure of

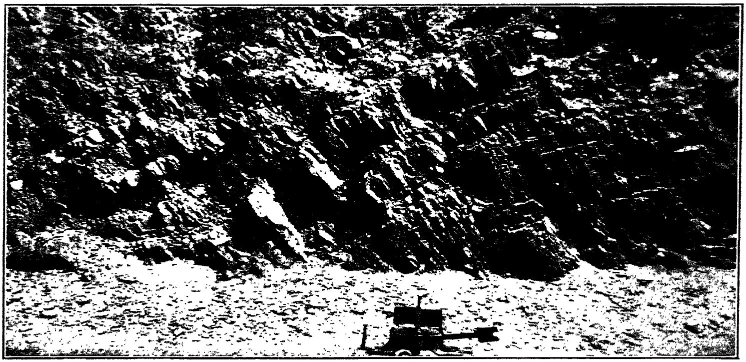

FIG. 241. — Fissile rocks, Lehigh Gap, Penn. (Geol. Surv., Penn.)

a cleaved slate is also clear evidence of strong compression, but there is some difference of opinion as to the direction in which the force acted. Both observation and experiment with clay and wax agree in indicating that cleavage planes are normal to the stress, and most geologists accept this view, though some maintain that cleavage develops along the shearing planes.

Fracture Cleavage, Fissility. To a certain extent, these are synonymous terms. In fissile rocks the parting into parallel laminæ is not merely potential, but has actually taken place along the shearing planes and the laminæ are therefore steeply inclined, at angles of 45° or more, to the direction of the compressing stress. In fracture cleavage, by definition, the partings have been closed

by cementing, or welding, and has become potential. In a series of strongly compressed rocks flow cleavage is produced in the softer, finer-grained beds in planes normal to the line of compression, fracture cleavage in firmer and coarser rocks and along the shearing planes.

B. Unconformity and Overlap

We have hitherto considered the stratified rocks as being made up of beds which follow upon one another in orderly sequence, all affected alike by any disturbance, diastrophic movement, folding

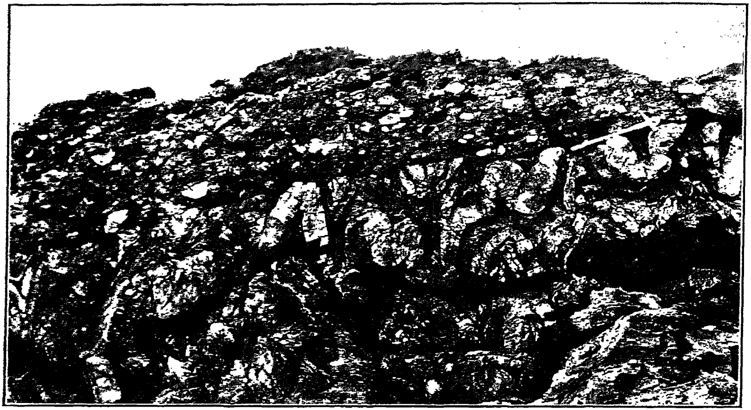

Fig. 242. — Angular unconformity, old red conglomerate lying on truncated folds of slates and limestones, Island of Kerren, Oban, Scotland. (Geol. Surv. Gt. Brit.)

or faulting, to which they may have been subjected. Strata which have thus been laid down in uninterrupted succession, have sensibly parallel bedding planes, and have been similarly affected by disturbances are said to be *conformable* and the structure is one of *conformity*. It frequently happens, however, that, in an exposed section, the beds are obviously divisible into two groups, each one made up of a series of conformable beds, but the upper group, as a whole, is not conformable with the lower, for

it lies upon the upturned and truncated edges of the strata of the underlying group, or upon their eroded surfaces. In such a structure the two groups of beds are said to be *unconformable*, and the relation is one of unconformity.

The term *unconformity* is used for all kinds of discordance between superposed groups of stratified rocks, making distinctions for the various kinds of discordance.

FIG. 243. — Angular unconformity, horizontal Triassic beds on inclined Moine gneiss, Southwestern Mull, Scotland. (Geol. Surv. Gt. Brit.)

Angular unconformity, or *nonconformity*, indicates a difference of dip between the two series of beds, the upper resting upon the edges of the lower, though the difference is by no means so great in all cases. Sometimes the difference in dip is slight and hard to detect, in other instances it varies from point to point.

Disconformity is the term used when there is no difference of dip between the two sets of beds, the upper series laid down upon the worn and eroded surfaces of the lower.

In any kind of unconformity there has been an interruption in deposition between the two groups of strata, a time unrecorded in that area, which, from the geological point of view, may be

relatively short or unimaginably long. On account of this break in the records, unconformities were relied upon to demarcate the major divisions of geological time, in the early history of the science. It so happened that in northwestern Europe, then the only part of the world geologically known, unconformities were very conveniently spaced for this purpose, but they are not, as was at first supposed to be the case, of world-wide extent. This is a fortunate circumstance, for the gaps in the record of one region are, in large degree, filled in from the continuous record of another.

Unconformities may occur in any kinds of stratified rocks, or between stratified and massive rocks, but the most significant breaks are those between groups of marine beds, and, under such conditions, the interpretation of an angular unconformity is as follows: (1) The most ancient series of beds was laid down upon the sea bottom in water of shallow or moderate depth. (2) The sea bottom was then raised by a diastrophic movement into land, either folded, tilted, or faulted and dislocated. (3) The new land surface was attacked by denudation, the folds truncated, tilted beds planed down to a surface, fault scarps removed. Yet if the new land surface was raised very little above sea-level denudation might have acted with extreme slowness. (4) The land surface was again depressed and was inundated by the sea, upon the bottom of which the second and overlying series of strata were deposited. (5) The whole area was finally raised into land and a newly cut relief in cliffs, and cañons made sections through the newer series and down into the older series, exposing the nature of the contact between them. Between the two groups of strata involved in an unconformity, there may be an immense lapse of time; in some well-known instances, countless millions of years undoubtedly passed between the formation of the older and of the newer series of beds.

Disconformity. The meaning of an unconformity of this type is essentially the same as in the angular kind; there is no difference in dip between the two sets of beds, because both sets are horizontal and without dip, or, if tilted, both sets were tilted together. The upheaval of the older group was not accompanied by tilting, faulting, or folding, and erosion carved a sculptured relief, which has been worn down to very small irregularities before the renewed transgression of the sea and the deposition of the upper series of beds.

It sometimes happens that, in the erosion of a series of horizontal beds, denudation may long be halted by the uncovering of an especially hard and resistant bed, especially if that hard bed lies at or but little above base-level. When the sea returns and sweeps away the soil which has gathered upon the resistant stratum, laying bare its surface, which then formed the sea bottom, and deposition was renewed, the upper series may appear to succeed the lower without a break. This is called a *deceptive conformity*,

FIG. 244. — Disconformity between Cretaceous (below) and Eocene strata near La Jolla, Calif. (Photograph by Arnold, U. S. G. S.)

and the real gap in time may easily be overlooked, especially if, when deposition was renewed, the same kind of material was laid down as that of which the hard bed is composed. In the Rocky Mountain region there are many exposures where a Carboniferous limestone seems to follow immediately upon one of Ordovician date, with no visible break except in the contained fossils. Here the many million years of the Silurian and Devonian are unrecorded, with apparently nothing to indicate the omission. When such deceptive conformities are traced far enough, however, their real nature is generally revealed by finding a disconformable contact.

The existence of a disconformity, when none is apparent, may sometimes be detected by finding structures which affect the lower and older but not the upper group of beds. For example, the lower series of strata may be faulted, or intersected by a dyke of igneous rock, the fault, or dyke, ending abruptly at a certain level, when it might be expected to rise higher; there is an indication of a concealed disconformity. If there are several such structures in the lower beds and all end suddenly at a particular level, the disconformity is almost certain. The lowest member in the upper series of strata in an unconformity is very frequently a conglomerate, or coarse sandstone, and represents the beach formation, the sea advancing over the old land. These *basal conglomerates*, as they are called, while very characteristic, are not always present.

Overlap. When an eroded land surface is inundated by the sea, the depression is ordinarily a gradual one and the valleys are first submerged, the waters slowly rising, until the hilltops are covered. Deposition thus begins on the valley floors, and if there are sloping sides, each bed will extend farther than the one upon which it lies, and thus in a thick mass of strata, if the shelving bottom be gently inclined, the upper beds will extend far beyond the lower ones, or *overlap* them. Overlap also occurs where the sea is transgressing slowly across a subsiding land surface, the rate of depression not much exceeding that of deposition. Here also each stratum extends farther across the old land surface than the one beneath it and conceals the edge of the latter. The relation of overlap is between the successive beds of a *conformable* series.

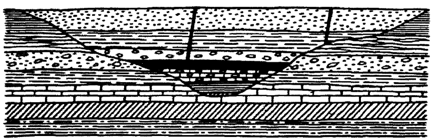

FIG. 245. - Diagram of disconformity and overlap.

Overlap may be of much practical importance, if one of the lower strata should be of economic value, such as a coal seam, for example. As Fig. 245 shows, there is nothing on the surface of the ground to indicate that the coal does not extend as far as the sandstone at the top section, except the contact between that sandstone and the shale bed which forms the summit of the older series. That contact might suggest a fault, or an overlap, and,

in either case, the advisability of making an exploratory boring with a diamond drill before sinking a costly shaft is clear.

Unconformities may exist on any scale; they may be local, or extend over a continent; a few would seem to be nearly universal and affect all lands.

Contemporaneous Erosion. The definition of unconformity, as given above, includes certain structures which it is important to distinguish as having an altogether different significance. One of these structures is contemporaneous erosion; this is produced when a current of water excavates a channel for itself in a still soft and submerged mass of sediments. After the current has ceased to flow, or has been diverted, renewed deposition fills up the hollow with material which is generally of the same character as that which was thrown down before, but is sometimes different, because of a change in conditions. Erosion of this kind involves only a short pause in deposition, not a long, unrecorded interval, nor is any diastrophic movement of elevation or depression required to produce the structure. Furthermore, contemporaneous erosion is a local phenomenon and, though in a limited section, it may not always be easy to distinguish it from a true disconformity, the difference becomes plain when a wider area is examined. If the structure is an example of contemporaneous erosion, the two series of strata will be conformable except along the line of the channel.

The clay *horses*, as miners call them, which frequently interrupt coal seams, are the channels of streams which meandered through the ancient peat bog and were filled with sediment when the bog became submerged. The horses are usually of the same rock as that which forms the cap or roof of the coal bed.

In the vast areas of river deposits, of Tertiary date, which cover so much of the Great Plains from Canada to Mexico, are great numbers of filled channels exposed in the wild and extravagant erosional forms of the bad lands. These channels, cut through the regularly stratified deposits of the flood plains, are filled with coarser materials, indurated pebbles and cross-bedded sandstones, and, on casual inspection, might be thought to be unconformities, but they are contemporaneous with the beds through which they are cut.

Cross Bedding. Another kind of deceptive resemblance to angular unconformity is occasionally caused by the alternation

of horizontal and oblique bedding in deltas or current deposits, a horizontal bed resting upon the upturned edges of a series of inclined layers. A conspicuous illustration of this is afforded by the Le Clair limestone of Iowa, which was, at one time, entirely misunderstood. It is usually not difficult, however, to recognize the true meaning of this structure.

Outliers. An outlier is an isolated mass of strata which is surrounded on all sides by beds older than itself. Not that the older beds must actually rise to the level of the outlier and inclose it bodily, but, as *viewed on a geological map,* which brings all irregularities down to one plane, the older beds appear to surround the outlier. The latter has been cut off by denudation from its former connections, from which it is separated by almost any distance, a few feet or a great many miles. Outliers are thus monuments which show, partially at least, the former extension of strata which have long been subject to erosion, though it is never certain that the farthest outlier was at the original margin, and one may generally be confident that it was not. It gives, however, a line for the minimum extension of the beds. In the later part of the Cretaceous period North America was cut into two parts by a sea, which extended from the Gulf of Mexico to the Arctic Ocean. The present eastern border of the rocks deposited in that sea runs through western Kansas and Nebraska, but outliers in Minnesota and Iowa show that the shore line was near the present line of the Mississippi River. Outliers are nearly always made up of horizontal strata, or of isolated synclines.

A *faulted outlier* is one that is due to faulting rather than erosion. A faulted outlier may be found on the downthrow side of a fault, especially in a trench, which is on the downthrow with reference to the blocks on each side of it.

Inliers differ from outliers in not necessarily being isolated *masses* of strata, but merely isolated *outcrops* of older beds, which are inclosed in new strata, though underground they may be continuous with very large areas of beds. An inlier is thus a larger or smaller mass of strata surrounded by beds which are geologically younger than itself. The summit of an anticline or dome which has been truncated by erosion exposes older strata in the middle, newer ones on the sides. There are also faulted inliers, which are found on the upthrow side, especially of a horst, which is on the upthrow with reference to both sides of the block.

When the projecting scarp has been planed away, older beds are flanked on both sides by newer ones, all at the same level.

Outliers may be converted into inliers by the deposition of newer beds around them. The isolated stacks and pillars on the sea coast, such as are seen in Figs. 168 and 169, are outliers, but a downward movement, submerging them under the sea, would result in surrounding them with later deposits and thus convert them into inliers.

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CHAPTER XXI

STRUCTURE AND ORIGIN OF MOUNTAIN RANGES

The word *mountain* is loosely employed in popular speech for any high land, the summit area of which is small, as compared with a plateau. In such usage the distinction between mountain and hill is a question of height and therefore one class grades into the other. Some so-called mountain peaks and ridges are but fragments of dissected plateaus, such as Lookout Mountain and Missionary Ridge in Tennessee, the Allegheny Front in Pennsylvania, Table Mountain at Cape Town, and many others. Such mountains usually have flat tops, and are made up of nearly or quite horizontal beds and owe their existence either to their being composed of more resistant rocks or, much more frequently, to their situation with reference to the drainage lines.

Another type of mountain is the volcanic cone which may be built up to great heights and arranged in linear series. A volcanic cone is the heap of material, fluid or fragmental, brought up from the earth's interior and piled up around the vent. The Absaroka, or Shoshone Mountains, a short range which runs north and south through the eastern part of the Yellowstone Park, is sculptured from a mass of volcanic agglomerate, piled upon a platform of sedimentary rock. This very unusual mass is, by some geologists, believed to be due to explosive fissure eruptions, others derive it all from one gigantic crater. In some instances, the molten magmas have pushed up a dome of strata, instead of breaking through in a volcano. Such domes, with cores of plutonic rock, are called laccoliths (p. 78), and may occur separately, as in the scattered ones of South Dakota, northeast of the Black Hills, or in groups (Henry Mountains of southern Utah), or they may form extensive parts of true ranges (Elk Mountains, Colorado).

A third class of mountains are the block mountains, which are carved out of tilted fault blocks and in which folding may or may

not be involved. The *Basin Ranges*, short parallel ranges in the Great Basin (Nevada), are typical examples of block ranges, and Ruwenzori, which rises out of the western Rift Valley of central Africa, is a fault block. The Coast Range of California, though its strata are considerably folded, is yet principally a series of fault blocks. The latest study of that range enumerates and maps fifty-seven faults and twenty-four blocks in the middle part of the state, south of San Francisco. (Clark.)

The lofty St. Elias Alps of southeastern Alaska are formed from a tilted block. Block ranges are comparatively short and few of them are of great height.

The great ranges of the earth are, so far as they have been studied, mountains of *folding* and differ materially from the preceding classes both in structure and mode of origin, though in certain instances, as in the Sierra Nevada of California, both folding and faulting had a share in forming the range. Certain terms used in the description of mountains of folding must be defined as a preliminary, with the proviso, however, that there is little uniformity or exactitude in the use of these terms by various writers.

A *Mountain Range* is made up of a series of more or less parallel ridges, all of which were formed within the limits of a single geosyncline (see p. 422) or on its borders. The ridges are separated from one another by longitudinal valleys and may be formed by the anticlines or, in more eroded ranges, by the outcropping of the more resistant structures, or strata. A true mountain range is always very long in proportion to its breadth, and its ridges have a persistent trend. These characteristics distinguish a range of folding from the ridges carved out of a plateau by denudation. The Appalachian, Wasatch, and Uinta, Front Range of Colorado, the Pyrenees, Carpathians, etc., etc., are well-known examples.

A *Mountain System* is made up of a number of parallel or consecutive ranges, formed in different geosynclines, but of approximately similar dates of upheaval. The Appalachian system includes the Appalachian range, running from New York to Georgia, and the Ouachita range of Arkansas and Oklahoma. The Acadian range in Nova Scotia and New Brunswick is usually regarded as part of the Appalachian system, but Professor Schuchert has recently given strong reasons for regarding it as much earlier in date. The Rocky Mountain system includes the many

ranges of Colorado, Wyoming, Montana, and western Canada, though the geological date of many of these ranges has not been precisely determined.

A *Mountain Chain* comprises two or more systems in the same general region of upheaval. The Appalachian chain includes the Appalachian system, the Blue Ridge, the Highlands of New Jersey and the Hudson, the Taconic system of western New England, the Green and White Mountains of Vermont and New Hampshire, and the Acadian range of Nova Scotia and New Brunswick.

A *Cordillera* consists of the several ranges, systems, and chains, whatever their geosynclinal relations and dates of formation, that, having the same general trend, occur in the same region of a continent very broadly considered. Thus all the mountains of the Pacific Coast and Western Interior regions, the Rocky Mountains, Wasatch, Uinta, Basin Ranges, Sierra Nevada, Cascades, and Coast Ranges and their continuations in Canada and Alaska make the *Rocky Mountain*, or *Western Cordillera.* The term is Spanish and means simply a range or chain of mountains, but is technically employed in this country for the whole broad band of mountainous systems and chains which cover a belt nearly 1,000 miles wide on the Pacific side of the continent.

The unity of structure and origin of the mountain range make it an especially favorable subject for the study of the general problem of mountains.

Leaving aside for the present the block mountains, a folded range consists of a very thick mass of strata; in the Appalachians the thickness of the beds varies from 25,000 to 40,000 feet. Beyond the folded and overthrust area, the same beds may be traced westward to the Mississippi Valley, where they are very much thinner, hardly more than a tenth as thick as they are in the mountains. This immense thickness of the component strata is everywhere characteristic of folded mountains; the Wasatch range has 31,000 feet of strata, the Alps 50,000 feet, etc. The strata of a mountain range are usually conformable, though the conformity is sometimes deceptive and due to the obliteration of unconformities by folding.

A universal feature of mountain ranges, other than block mountains, is the intense compression and folding of the strata, often accompanied by great thrusts and by intrusions of igneous rocks. There is very great difference between the various ranges with regard to the degree of compression to which they have been

subjected. The Uinta range is formed by a single immense and gently swelling anticline, which has its axis east and west, with a great strike fault along the northern base. The curvature of the beds is so gentle that, except on the flanks, they seem to be nearly horizontal. The Black Hills of South Dakota are an oval dome, or an anticline with very short axis; the dome has been profoundly dissected, the higher, overarching strata removed from the summit of the dome and the granite batholith exposed and eroded. The highest point in the Hills, Harney's Peak, is formed by the "needles" of granite.

Such single structures as the Uintas and the Black Hills are exceptional. In the typical mountain range the strata are compressed into a series of parallel folds, which may be open, upright, and symmetrical, as in some of the ridges of the Jura Mountains of northern Switzerland. In these the folding is so regular that a cross-section, such as may be seen in the river gorges, looks like a diagram. Much more commonly the compression has been very intense, causing the strata to form closed, asymmetrical, overturned, and even recumbent folds. In the Appalachians, where the compression was not nearly so extreme as in many other mountain ranges, these overturned and recumbent folds, accompanied by great thrusts, are abundantly displayed. In the Sierra Nevada (California) the plication is so complicated that the thickness of the strata has not been determined.

The Alps have been studied with the utmost care by a host of brilliant geologists, most of them, of course, Swiss and Austrians, but so unimaginably complex is the structure of these ranges that a comprehension of them has but lately been emerging from the confusion. The recumbent and extraordinarily elongated folds and the oft-repeated overthrusting have produced results that make the Appalachian structure seem to be simplicity itself. The Himalayas, highest of all existing mountains, have been crumpled and overthrust from the north, but the structure, still incompletely known, seems to be much less complicated than that of the Alps.

In folded mountain ranges three zones may be distinguished: (1) A rigid, unyielding mass, which is not folded; (2) the zone of folding; (3) the zone of diminishing action, where the folding gradually comes to an end or is abruptly cut off by faults. Many, perhaps most, ranges are bounded by faults on one side or the

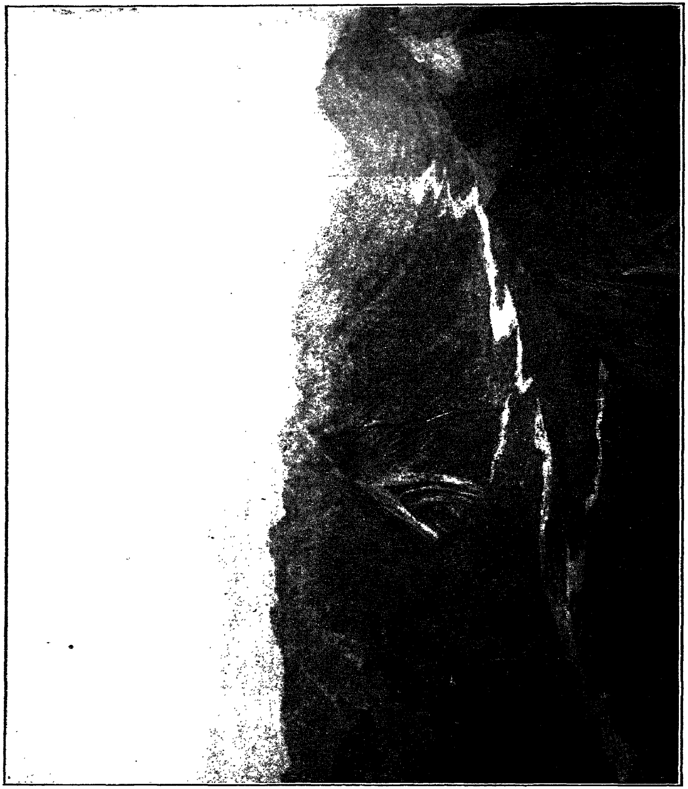


FIG. 246. — Anticlinal ridge, Mountain Park area, Alberta. (Geol. Surv., Canada)

other, as is true of the Sierra Nevada, Wasatch, and Uinta mountains. The mass toward which the overturned folds incline is called the *foreland* and may comprise either the rigid, unfolded rocks or the zone of diminishing action, and the side from which the compressing force seems to act is called by the German word *Hinterland*, for which there is no English equivalent. A literal translation, "back country," has quite a different connotation. In the Appalachians the foreland is the zone of diminishing action and on the western side of the mountains; in the Alps this

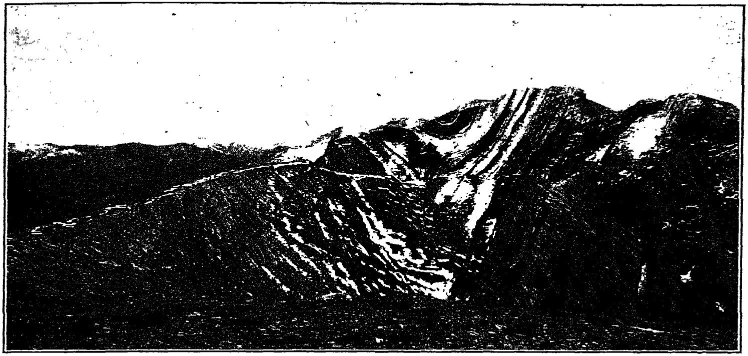


FIG. 247. — Synclinal ridge, Mt. Perdrix, Alberta. (Geol. Surv., Canada)

arrangement is reversed: the foreland is the resistant mass, on the north; the hinterland the zone of diminishing action on the south. In the Himalayas the foreland is on the south; the hinterland, the unyielding mass of the Tibetan plateau, is on the north. In both Alps and Appalachians the foreland was away from the sea, from the direction of which the folding force would seem to have acted.

The two main characteristics of folded mountain ranges are: (1) the immense thickness of the strata of which they are built up, much greater than that of the same strata in unfolded regions, and (2) the compression and folding or thrusting to which they have been subjected. Certain accessory structures, also dependent upon compression, should be mentioned: (*a*) The major folds,

of the first order, are themselves made up of successive series of minor folds in descending magnitude, the smallest of them visible only under the microscope. (*b*) Dynamic metamorphism is a very general feature of mountain ranges, though not universal; cleavage of slates and fissility of sheared beds is a feature of the metamorphism. The microscope shows impressively how enormous the force of compression must have been, the mineral particles mashed and shattered and often rendered plastic and flowing like wax or wet clay in a press. (*c*) Intrusions or extrusions of igneous rocks, or both, are very often associated with mountain ranges, but such association is not invariable. Most of the Appalachian range has no igneous rocks in it and none are known in the Uintas. Many ranges, on the other hand, have a batholith of granite as a core. The strata which once arched over the core have, for the most part, been removed by denudation and are now confined to the flanks of the batholith and hence the highest crests and peaks are of granite. This is the case in the main range of the Rockies and the Sierra Nevada; the batholith in the Black Hills, which appears in Harney's Peak, is far older than the stratified rocks and would seem to have been uplifted with them.

A. Origin of Mountain Ranges

The manner in which the true ranges of folding have been brought into being must be deduced from a study of their structure; for direct observation of the processes is impossible, partly because they are deep seated, but chiefly because they are so extremely slow. Mountain building may be going on at the present moment; indeed, there is no convincing reason for supposing that it is not, but it is impossible to verify such a suggestion. If there is anywhere an incipient range, its birth and growth are entirely withdrawn from observation. If antecedent rivers have been properly interpreted (p. 286), they demonstrate the slowness with which mountain ranges are raised across the path of streams, so that the streams can cut through the rising obstacles at least as fast as the folds go up and are not diverted from their course. All over the world rivers appear to take impossible courses and cut through mountains instead of avoiding them, which is best explained on the assumption that, in such instances, the rivers are older than the ranges.

Not very long ago it was generally believed by geologists that "the general course of events in the history of a range may be inferred with much confidence from its structure," but this belief is now widely questioned and rival theories have been propounded as solutions of the problem. Not only is there dissension as to the origin of the compressive force, but the actual events and the order of their succession have been called in question.

The first step in the formation of a mountain range was, in nearly all cases, the accumulation of an immensely thick body of strata, which must have taken place chiefly under water and in the sea. The study of modern deposition shows that very thick accumulations are made in various depths of rather shoal water and parallel with shore lines. In mountain ranges there are very thick beds of conglomerates, coarse sandstones, ripple-marked strata of all materials, sandstones, shales, even limestones, and sun-cracked sediments. Deposits laid down in the deltas and on the flood plains of rivers add their quota, but chiefly shallow seas and lines parallel with the coasts are the areas of most rapid deposition and in greatest quantity. For the accumulation of very thick sediments in shoal water, it is necessary that the bottom subside isostatically as fast as the deposits are laid down, otherwise the water would be filled up and deposition cease along that line. Such a subsiding, sediment-filled trough is a geosyncline (p. 422), and in geosynclines is the cradle of the typical mountain range. The area of the trough varies from time to time in length and breadth, as do also the position of the line of maximum subsidence and the relative rate of depression and sedimentation, causing variations in the depth of water.

The second stage in the formation of a mountain range is folding by lateral compression, which makes the sides of the geosynclinal trough approach each other as do the jaws of a vise, crumpling the contained sediments into folds. This crumpling is not a single operation, but is repeated a greater or less number of times throughout a long period, and the effect of it is one of the many disputed questions which are involved in the history of mountain ranges. According to the more generally accepted view, the first effect of the folding was to shorten the width of the folded belt and increase its height, the anticlines forming mountain ridges and the synclines valleys, as they do in the Jura Mountains of today. That the earth's circumference has been reduced in the

mountain belts, is not disputed, for the strata were originally laid down in horizontal attitudes, a necessary consequence of gravity, as was previously pointed out (p. 415), and folding brings their ends nearer together, which is as much as to say, diminishes their breadth transversely to the folds.

Recent reëxaminations and measurements have shown that the reduction in breadth of many mountain ranges by the act of crumpling had been considerably underestimated. Thus for the Alps, the narrowing of the belt due to the Tertiary folding is from 120 to 180 miles (Heim); for the Appalachians 190 miles (Keith); and in the Rockies a single thrust with a displacement of 35 miles has lately been discovered (Mansfield). Remembering that repeated compression, with folding and thrusting have elevated the ridges, there is another movement which has much increased the height of certain mountain ranges, perhaps of ranges in general, and that is direct vertical uplift. It is seldom easy to prove this upheaval, but in some instances it is quite certain and in others very probable. One of the clearest cases is that of the southern Andes, which in Patagonia show a rise of 5,000 feet since the late Pliocene Tertiary. Marine beds of that date are found in the Andean foothills 5,000 feet above sea-level. In the mountains of Bolivia are found tropical plants in a fossil state embedded in strata at altitudes far above the level at which they could exist at present. Such occurrences might, of course, be explained by a change of climate, but such change is improbable. There is much reason to believe that vertical uplift is a normal part of the development of mountain ranges as well as the folding and faulting which are to be seen in all true ranges.

The generation of the compressive force, to which folding and thrusting are due, is a highly controversial subject. For a long time the matter seemed perfectly clear and simple; the secular cooling of the earth was believed to cause contraction of the subcrustal interior, and the crust, which could not support itself, was forced to follow a shrinking interior for which it was too large. Being thus crowded into a smaller space, horizontal stresses were set up, which accounted for all the shortening of the crust, the narrowing of folded belts, and the crumpling of the sedimentary masses contained in the geosynclinal troughs. For the lack of a better explanation, many geologists still maintain the contraction hypothesis, but many reject it altogether, chiefly for two reasons.

In the first place, it is denied that the compression due to cooling and shrinkage is adequate to produce the observed effects; and, secondly, owing to the heating of the interior by radio-activity, it is questionable whether the earth is cooling and shrinking at all. Other and minor difficulties are found in the contraction hypothesis, but the two mentioned are regarded by many as fatal to it. Recently, the hypothesis has been rehabilitated by Dr. Harold Jeffreys, of Cambridge, in the second edition of his admirable book, *The Earth* (1929). He says: "Of the many causes of mountain ranges that have been proposed, only two have been shown adequate to account for any appreciable fraction of the crumpling that has occurred, and many are even qualitatively as well as quantitatively unsatisfactory. The most effective seem to be thermal contraction and changes in the rotation of the earth." (P. 278.) The latter agency, it should be said at once, enters hardly, if at all, into geological history and need not be considered, as it is rather an astronomical question. "The available compression would therefore appear ample and perhaps, indeed, embarrassingly superfluous, if the geological estimates of the observed compression had not recently been so much increased." (*Ibid.*, p. 282.) "On the whole it seems that the agreement between the actual and predicted amounts of compression is as good as could be expected." (P. 284.)

An exceptional mountain system, which casts a doubt upon the whole theory of mountain making, is the Caledonian, which followed a nearly semicircular curve and the folding of which went on during almost the whole Silurian period. The principal curve ran from Ireland across England and Scotland, through Scandinavia, Spitsbergen, Greenland, Ellesmere Land, and northern Alaska. As Born points out, the Caledonian ranges were not due to the compression of a geosynclinal trough, filled with sediment. "A Caledonian geosyncline, in the form of the Caledonian mountain ranges, never existed. The folding affected, in part, marine areas of heavy sedimentation and, in part, the margins of the continents," thus differing from all other known ranges.

In the Scandinavian mountain ranges which form part of the great Caledonian folding, the structure has been exposed by very profound denudation. The intensity of compression diminishes downward, and where the underlying foundation of Pre-Cambrian rocks had been worn down to a smooth peneplain before the deposi-

tion of the Palæozoic sediments, the Pre-Cambrian was hardly affected by the folding. Where the surface was irregular, blocks of the crystalline rocks are included in the Caledonian folds. Steinmann reports similar observations in the southern Andes, where strata violently compressed have yielded by folding and, at the same time, gliding over a "sole" of crystalline rock, apparently Pre-Cambrian.

An alternative explanation of the origin of mountain ranges is derived from the Taylor-Wegener hypothesis of continental drift

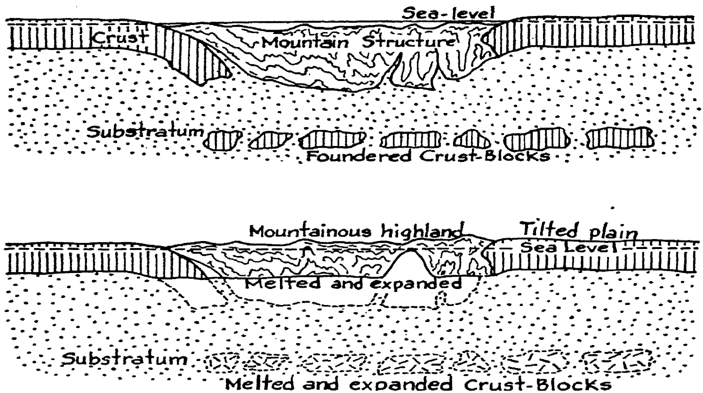


FIG. 248. — Diagrams illustrating the chief cause of mountain height. (Daly)

and is developed by Professor R. A. Daly in his *Our Mobile Earth.* This explanation assumes the formation of geosynclines, and the genesis of lateral compression by the secular cooling and contraction of the earth which has distorted the surface of the earth and continental drift is occasioned by the downhill sliding toward the geosynclines, crumpling their contained sediments. Beneath the geosynclines the crust gave way and its fragments sank into the hot substratum, while the folded mass of sediments was *pushed down* into the substratum, and thus the ranges do not owe their height to folding, but to later direct upheaval. This vertical uplift was caused by the melting and expansion of the foundered

crust blocks and the "roots" of the mountains through the ascent of the earth's internal heat.

The *Geological Date of Mountain Ranges* means the period in geological chronology when the principal folding took place; this date is subsequent to the newest strata involved in it and antecedent to the oldest strata which did not take part in the movement, but must have done so had they been present. Strata which rest unconformably, or with overlap, against the flanks of a range must have been deposited after the folding had been effected. If the newest folded and the oldest unfolded strata be of successive geological periods, the date of the mountain formation is placed between those two periods and is said to close the more ancient period for the particular region involved. The history of a mountain range after its final elevation above the sea must be made out from its denudation and the development of its drainage and topography.

The formation of mountain ranges was not a continuous process, but was a frequently recurrent one, with long periods of quiescence. Aside from the pre-Cambrian periods, when mountain making seems to have been well-nigh universal over the continents, there are in the history of North America well-defined times of diastrophic movements of compression. The northeastern part of the continent was profoundly affected by the Taconian (or Taconic) orogenic activities which, on the principles explained above, are regarded as having closed the Ordovician period and to which the mountains of New England are due. The "Appalachian Revolution," as it is called, throughout the later Carboniferous period, was active in producing folds in the great geosyncline, the final compression of which generated the Appalachians from New York to Alabama and the Ouachita range of Arkansas, closing the Permian Period and Palæozoic Era for eastern North America. The Sierra Nevada received its initial form from a post-Jurassic compression, but was greatly modified subsequently. The Rocky Mountains and the Andes were folded in post-Cretaceous time, but the culminating upheavals came in the succeeding Tertiary period, which was the great time of mountain making in the Old World, when the ranges of northwestern Africa and of southern Europe and Asia were developed. The Pyrenees, the Apennines, the Alps, Carpathians, Balkans, Caucausus, and Himalayas are a gigantic chain of Tertiary date, while in California and Alaska

are ranges of Quaternary date. Orogenic disturbances do not seem to have been periodic, in the sense of rhythmically recurrent, but there were very definitely marked times of orogenic activity separated by periods when the compressive stresses were accumulating very slowly until the resistant strength of the rocks was overcome.

B. Denudation of Mountain Ranges

Mountain ranges, as they are at present, never display the form which they would have if only the forces of compression and elevation had been concerned in the making of them. Though many are, geologically speaking, very young, none has escaped the profoundly modifying effects of erosion, and mountain topography is proverbially rugged and broken. The ridges, knife crests, and peaks have been carved out of swelling folds and domes, or from angular, tilted fault-blocks. It is not a coincidence that all the very lofty ranges of the earth are of late geological date. The Alps and the Himalayas, the St. Elias Range, are all of Tertiary and even post-Tertiary date and they, especially the Himalayas, are of great height. The Andes, also a very lofty range, had their last upheaval late in the Tertiary period, and their highest peaks are volcanic cones. On the other hand, the geologically ancient ranges, such as the Appalachians, the mountains of northern Europe, the Urals, etc., are all low; denudation has so cut them down that they are now but stumps of what they once were. Erosion must have begun its destructive work as soon as the ridges first appeared above the sea, or above the level of the ground. Very probably no range of folding ever had the full height which the strata, if not attacked by denudation, would have given it.

Upheaval, though often so slow as to enable rivers to keep their channels open, was yet too rapid to be kept in check by general atmospheric weathering and so the ranges have grown to great heights. As soon as upheaval ceased, denudation began to get the upper hand, for in high mountains destruction is especially rapid. Above the level of the growth of trees (timber-line, it is called in this country) there is usually a zone of grass land, remarkable for the abundance and beauty of its flowers, and above that again the naked rock is exposed without protection of soil and vegetation to the violent action of frost, as is vividly shown by the

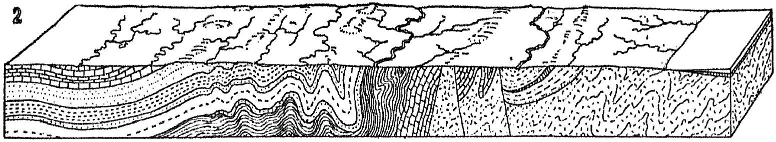
immense talus slopes of all high mountains. The wind, which often blows with great fury, is an active destroyer in these cold and stony deserts, and the undermining action of springs so often causes vast rock slides and the fall of whole peaks that many have been seen by eye-witnesses within the last century.

Especially effective as agents of destruction in high mountains are snow and ice. Avalanches carry down vast quantities of rock to the valleys, and snowbanks, by the process of nivation, begin the formation of cirques, which become the gathering grounds and sources of glaciers. When several glaciers form on the different sides of a mountain, the recession of the cirques reduces the peak to sharp crests and knife edges. The early stages of this process may be seen to great advantage in the Bighorn Mountains of Wyoming and the Uinta range of Utah, and, in much more advanced degree, in the Alps and the Sierra Nevada, the extreme ruggedness of which is largely due to the formation and recession of cirques.

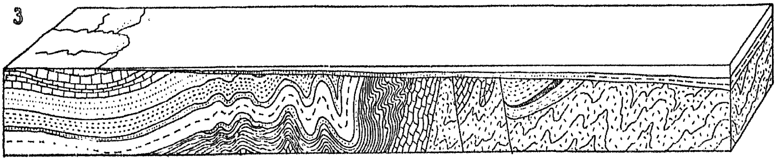
For a long period, the effect of the denuding agents is greatly to increase the roughness and irregularity of mountain topography, carving folds into ridges and ridges into bold and inaccessible peaks, but they are constantly losing height and are worn down lower and lower, until eventually they are leveled with the plains from which they spring. In the process of degradation synclines often resist longer than anticlines, which are cut below them and, thus standing in relief, form the synclinal ridges of many ancient ranges. The degradation may go so far as to cut down a range to its very roots, leaving only the intensely folded strata of the peneplain as evidence that mountains ever existed there. Of such a nature is the upland of New England and the great metamorphic area of Canada, both of which probably had high ranges of mountains in very ancient times.

C. Appalachian Cycles

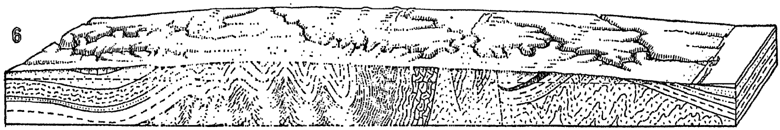
Any region, however lofty and however rugged, must sooner or later be worn down to base level, provided only that the region remain stationary with reference to the sea, until the process of degradation is complete. However, it is doubtful whether any large area of hard rocks has ever been actually reduced to base level; the usual result is the formation of a peneplain, a low-lying, more or less undulating and nearly featureless surface, with only



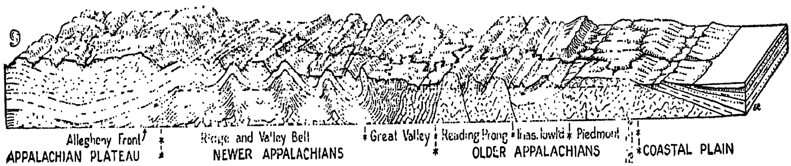
The Fall Zone peneplane.



Encroachment of Cretaceous sea and deposition of coastal plain beds.



Arching of Schooley peneplane.



Uplift and dissection of Somerville peneplane to give present conditions.

FIG. 249. — Block diagrams illustrating Appalachian cycles. (D. W. Johnson)

occasional eminences rising above the general level. Reëlevation of a peneplain at once revivifies the streams and renews the activities of all the denuding agents, for gravity is the essential motive power of running water, and atmospheric disintegration and decomposition are checked by the accumulation of débris. Even the sea acts less effectively on a low, flat coast than on a high, bold one and works with renewed power when the land is elevated. A peneplain raised into a plateau is again dissected, as before, first by the rapid downcutting of the stream valleys to a new base level, while the divides between streams are much more slowly removed. If time enough be given, and the new plateau be of sufficient altitude, the upland is first dissected into strong relief and then the relief is planed away to a new peneplain. The development of relief and then its removal, from peneplain back to peneplain, constitute a cycle of denudation, which may be interrupted by a renewed upheaval before peneplanation is complete, and thus form an incomplete cycle. Through careful study of a region several incomplete cycles may be found, which are represented by remnants of dissected uplands at different levels, preserved in the harder rocks. The remains of the older plateaus have the greater altitude, having been raised at each diastrophic uplift.

The Appalachian range has been intensively studied for nearly a century, and though very much of its history remains to be deciphered, an outline of that history has been constructed, as to which the principal doubt concerns the geological date of the events. The range began as a great geosyncline on the margin of an inland sea, and in this relatively long and narrow trough, which was in shallow water, an immense thickness of sediments accumulated during the countless millions of years comprised in the Palæozoic Era. Diastrophic movements, with the formation of folds, took place repeatedly in the Carboniferous Period, but it was during and at the close of the last of the Palæozoic periods, the Permian, that the principal folding took place, accompanied by a general uplift of all the land east of the present line of the Mississippi River. In this great series of contractions, known as the *Appalachian Revolution*, the sides of the geosynclinal trough were moved toward each other for many miles, crushing and crumpling the mass of contained sediments into many roughly parallel, closed, and overturned folds, or breaking in overthrusts

and forming what was probably a lofty range of mountains, rivaling the present-day Rockies or Alps in height.

During the long ages of the Mesozoic Era, the mountains were profoundly denuded and worn down to a peneplain, with only a few residual hills, or monadnocks, rising above the almost featureless level, the highest of which are now the peaks of western North Carolina, such as Mt. Mitchell. A new interpretation of the events which followed this peneplanation has lately been suggested by Professor D. W. Johnson, to explain the river systems of the Appalachian region.

In the latter part of the Cretaceous period the coastal plain of the Atlantic and Gulf shores, from Massachusetts to Texas, was depressed by faulting or flexuring, and covered by the sea. So much is accepted by every one, for the Upper Cretaceous marine deposits are displayed for the entire length of the coastal plain and the boundary line of the Cretaceous outcrop is not far from the inland border of the plain. The particularly novel conception of Professor Johnson's hypothesis lies in the inference that the Upper Cretaceous sea transgressed over the entire worn-down Appalachian belt, which would bring it some 200 miles inland to the present border of the Cretaceous deposits. This is a wide departure from previous beliefs, but there is nothing at all impossible about it; the question is: does the entire body of evidence render this broad advance of the sea probable?

Assuming that the Upper Cretaceous sea did actually cover a belt some 175 to 250 miles wide, it follows that the entire belt must have received shoal-water marine deposits of no great thickness, but sufficient to bury the irregularities of the sea-floor; such as were due to the outcropping of harder ledges. When reëlevation occurred, no doubt, accompanied by a seaward tilting, there was a broad plain sloping gently to the sea and upon this plain were established the remarkable series of southeastwardly flowing rivers, from New England to Georgia. These rivers were, therefore, *consequent* streams, because their courses were determined by the original slope of the land, but, as they cut down through the covering of newly deposited marine sediments, they became *superimposed* and intrenched themselves so deeply that subsequent movements could not divert them. In this manner the hard ridges, buried beneath the covering of marine deposits, were cut through and the streams established as transverse rivers.

The subsequent history of the mountain range is too complicated to rehearse here in detail, for lack of space. It must suffice to say that the mountain belt was four times uplifted into a plateau, which was dissected into ridges and valleys and again reduced to a peneplain; remnants of these successive peneplains may still be identified, and they have been named the Fall Zone, Schooley, Harrisburg, and Somerville, in order of age. Through all these changes the master streams of those which flowed southeastwardly kept their courses, except as they were modified by capture

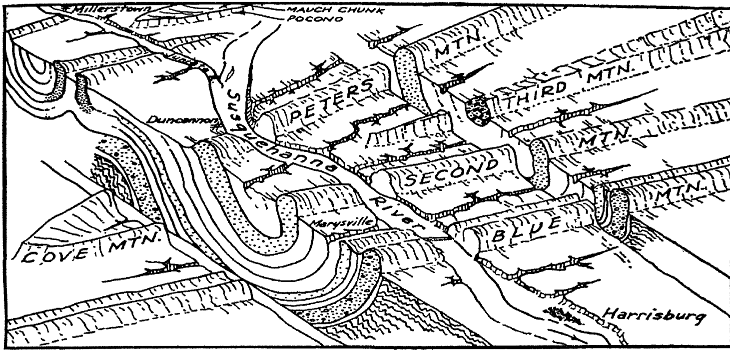


FIG. 250. — Block diagram of central Pennsylvania, showing how ridges are due to the outcropping of hard rock, canoe-valleys, etc. (Slightly modified from Lobeck)

and diversion. The number of wind gaps cut through the various ridges of the range, but no longer having streams flowing through them, is an eloquent testimony to the frequency of capture and diversion among the minor Appalachian streams.

An unusual characteristic of these mountains is their even, level sky-lines, without peaks or serrations, and running for many miles without interruption, save for an occasional stream gap. This is unlike almost any other mountain range and points to some very exceptional factor in the development of the Appalachians. Not only do the separate ridges have even and level summits, but they all have a nearly uniform height and they all, without exception, are composed of the hardest rocks. To recon-

struct the plateau formed by the reëlevation of the last peneplain, it is necessary only to fill, in imagination, all the valleys between the ridges up to the Allegheny Front on the west. The surface, so formed, would form a flat dome, arching extremely gently from east to west and from north to south. The highest point, some 1,700 feet, was in Virginia and the surface sloped away in both directions from that summit. Dissection of the plateau by the eroding agents, rejuvenated by the uplift of the region, rapidly carved out longitudinal valleys along the strike of the softer beds and established a series of longitudinal streams, while the southeastwardly flowing streams maintained their courses, thus becoming antecedent. According to Johnson's hypothesis, these major streams were first consequent, then superimposed, and finally antecedent in character. The transverse valleys, cut out by the major, southeastward streams, are narrow gorges, called "gaps," where they intersect the hard ridges, broad and with gently sloping sides, where they are on the softer rocks. The softer beds were worn down to one general level, as the period of quiescence, though long enough to reduce the less resistant rocks to this general level, did not suffice to lower materially the ridges of hard rocks. The relief of the mountains in their present form is only indirectly due to folding and directly to the differential erosion, which has carved valleys out along the softer strata, leaving the harder ones to project as ridges.

"The swelling of the Appalachian dome began again. It rose 200 feet in New Jersey, 600 feet in Pennsylvania, 1,700 feet in southern Virginia, and thence southward sloped to the Gulf of Mexico. . . . In consequence of the renewed elevation, the streams were revived, they have sawed and are sawing their channels down and are preparing for the development of a future base level." (Willis.)

The state geologist of Pennsylvania, Dr. G. H. Ashley, gives an interpretation of Appalachian history which departs widely from that explained above, especially in not postulating a transgression of the Upper Cretaceous sea over the base-leveled mountains, and in maintaining that the peneplains are all of much more recent date than has commonly been supposed, the oldest of them belonging to the middle Tertiary period. It may be possible to reconcile the two theses by assuming that the marine transgression over the worn-down mountains was Miocene and not Cretaceous.

The Thian Shan mountain range, or plateau, in central Asia, is in many respects an interesting counterpart to the Appalachians, for it presents in actual form stages of development which have been inferred for the Appalachians from a study of their structure and their drainage systems. Although it has not yet been possible to make any thoroughgoing examination of the central Asian mountains, or to show the former existence of a geosynclinal trough, certain salient facts of great importance have been learned from preliminary reconnaissances, especially those made by the Carnegie Institution.

In the later periods of the Palæozoic Era, the Devonian and Carboniferous periods, the region was under the sea, and great thicknesses of sediments, especially limestones, were deposited on the sea bed. At the end of the Palæozoic, or beginning of the Mesozoic, these strata were violently compressed and folded, in a manner that indicates the formation of a range of lofty mountains. Extensive intrusions of granite and basalt, which have cut through the Palæozoic strata, were presumably injected at the time of folding. Since the period of mountain-making, the region has been above the sea, for no marine beds of later date are known, except for a brief encroachment of the sea in Cretaceous and early Tertiary times. Long-continued denudation swept away the mountains and cut the whole region down to a peneplain which truncated all kinds of rocks, hard and soft, igneous and sedimentary, alike. The plateau of today is a great geanticline, raised and upwarped many thousands of feet since it was reduced to a peneplain. "It is a region of mountainous structure, and once of truly mountainous form, but it long ago reached old age and has since been uplifted to its present height with relatively little renewed folding of the strata. In structure it is still mountainous, but its present form and altitude are due to an uplift of the uniform kind which is usually associated with the formation of plateaus. Today it may best be described as a plateau; tomorrow, geologically speaking, when all the remnants of the uplifted peneplain surface and the last of the post-Palæozoic strata have been removed and dissection has gone far enough to produce strong relief, it will again become a typical mountain region of highly folded limestones.

"The broad ridge which lies along the northern border of the Thian Shan plateau is always covered with snow and most of its

passes are occupied by glaciers. A few of the summits have been sharpened into peaks by glacial action . . . but most of them are mere remnants of the old peneplain, separated by broad, but not very deep, valleys of glacial origin." (Huntington.)

"The deformation that the great peneplain has suffered in that part of its area which is now mountainous seems to have involved late or post-Tertiary movements of relatively local uplift, as in the Bural-bastan; or of much broader uplift, as south of Issik Kul; or of moderate warping, as in the branch of the Dsungarian Alatau; or of block faulting and tilting, as about the west end of Issik Kul." (Davis.)

The parallel with Appalachian history is obvious; except for the block-faulting and tilting, the Thian Shan is now in the same stage of development as were the Appalachians after the upwarping of the Kittatinny peneplain and before erosion had carved out the existing relief of outcropping ridges of hard rocks and longitudinal valleys excavated from the soft beds.

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CHAPTER XXII

METAMORPHIC ROCKS — METAMORPHISM

The metamorphic rocks were originally sedimentary or igneous, and have been more or less completely changed *in place* without decomposition or disintegration, usually with increased hardness and the genesis of new minerals. The rocks of this class display all gradations of change from merely greater hardness to a complete reconstruction with the formation of an entirely new set of component minerals. So complete and radical is the transformation in extremely metamorphosed rocks, that it is often impossible to say whether a given rock was originally igneous or sedimentary; the result may be the same in either case.

The minerals of metamorphic rocks are largely the same as those of sedimentary rocks, on the one hand, and igneous rocks, on the other, but certain ones, such as cyanite, staurolite, tremolite, wollastonite, grossularite, are chiefly or exclusively found in metamorphic rocks. The gem, pyrope, a magnesium-aluminium garnet, is found only in igneous rocks, such as peridotite, and grossularite, a calcium-aluminium garnet, occurs especially in metamorphic limestones.

A. Classification of Metamorphic Rocks

Metamorphic rocks are divisible into two very unequal groups, the non-foliated and the foliated. By foliation is meant the division of the rocks into rudely parallel planes or undulating surfaces, due to a segregation of minerals and the arrangement of one or more of them in parallel flakes. A structure, often conspicuously banded, is the result.

I. Non-Foliated Rocks

These rocks are due to a metamorphism less extreme than that which has produced the foliated group, and the important ones are of sedimentary origin, generally retaining their original stratification. Each of the three main divisions of sedimentary rocks

which are made according to the principal substance of their composition, has its equivalents in the metamorphic series.

1. *Quartzite* is the principal metamorphic representative of the siliceous sediments and is mainly derived from the metamorphosis of sandstone. Between the two kinds of rock are found such complete transitions that it is difficult to separate them. In a typical quartzite, the rock is crystalline and the quartz deposited around the original sand-grains is in optical continuity with them, though those grains may still be seen with the microscope. A broken surface shows a glassy luster and a splintery or conchoidal fracture, while in sandstone the structure is granular and the surface is matt, without luster. The additional quartz which has grown around the sand-grains has been brought into the rock from the outside in solution and may amount to one-sixth of the weight before metamorphism.

Quartzites also result from the metamorphism of conglomerates, and the pebbles are often much flattened by compression. If the sandstone or conglomerate contained impurities, clay, lime, magnesia, iron, etc., etc., as such rocks nearly always do, many new minerals may be generated and a foliated rock formed ; quartzite, mica schist, and gneiss are a series of gradations, though gneiss is often derived from an igneous original. Foliation is thus seen to be brought about by a more advanced degree of metamorphism, provided the necessary elements are present, but a pure siliceous sandstone cannot form a mica schist.

2. *Slate* is a hard, dense, and very fine-grained rock, derived from the moderate metamorphism of clay shale, fine arkose, or even volcanic tuffs. It splits into very thin laminæ and is therefore very extensively employed for roofs, so much so that "roofing slate" is a common name. This property of splitting is called *slaty cleavage,* to distinguish it from the cleavage of minerals, which is molecular. Both experiment and field observation show that slaty cleavage is a result of compression. (See p. 465.) On examining a piece of slate along a cleavage plane obliquely lighted, shining particles are visible scattered over the surface. The microscope shows that these particles are tiny flakes of mica.

3. *Phyllite* resembles slate in appearance and cleavage, but differs in having been metamorphosed in more advanced degree and containing more mica and sometimes also visible crystals of quartz, garnet, pyrite, etc. The cleavage planes are so covered

with spangles of the potash mica, called sericite, as to have a distinctly silvery appearance. Not all phyllites are of sedimentary origin, as some have been formed by intense compression and shearing of felsite and its tuffs, in which the feldspars have been converted into mica.

4. *Marble*, properly so called, is the metamorphic form of limestone, including the dolomites and magnesian limestones, in which the calcite and the mineral dolomite are recrystallized. The crystals are sometimes very small and if the rock is homogeneous, pure white, and of even grain, it is called *statuary marble*. Impurities in the original limestone, sometimes in very minute quantities, give rise to the endless varieties of colored marble, to many of which names have been given, mostly Italian, and these were, in general, known to the ancient Romans, who quarried ornamental stones all over the known world and made very extensive use of them. The characteristic "marbling" is due to mashing and flow structure, often with recrystallization after each mashing.

The colors of marble vary with the nature of the original impurities of the limestone. Organic matter becomes carbonized when heated, and if segregated, gives rise to veins of graphite which, in the form of black lines in a white marble, mark the lines of compression, or shearing and flow, along which the rock yielded. If the organic matter was disseminated through the rock, as in a bituminous limestone, black marble is the result. Red, yellow, and brown marbles, many of which are extremely beautiful, owe their color to varying proportions and compounds of iron.

Unlike quartzite and slate, the course of metamorphism and the resultant recrystallization has destroyed all trace of fossils which the limestone may have originally contained and nearly always all the bedding planes also, so that a body of marble is as massive as an igneous rock divided only by its joints.

As "marble" is a trade name, it has no exact meaning, as any limestone hard enough to take a polish and of good color and texture is called marble; limestones are frequently crystallized by surface waters, as modern coral rock often is. In these limestones which were crystallized by the action of water the fossils are preserved and the stratification is unaffected, and it would be manifestly a misnomer to call such rocks metamorphic.

Besides the coloring matter, present in small quantity, the parent limestone usually contained considerable proportions of sand,

clay, iron compounds, and, in the dolomites, magnesia. When such limestone is metamorphosed, a crop of new minerals is generated, especially when vapors and emanations from intruding igneous bodies also operate on the rock. From scattered minerals in a matrix of marble to a silicate rock, there is every transition, and a host of minerals are involved. *Garnet rock*, *epidote rock*, *pyroxene rock*, and jade are some of the rocks made from impure limestones by metamorphosis.

5. *Cipolino* is a marble containing so much mica that it may fairly be called foliated. This stone was much used by the Romans and may be seen in the walls and columns of many temples.

6. The *Ophicalcites* are a mixture of white calcite and green serpentine. These rocks are not thoroughly understood and would seem to have been formed in different ways. Some are almost certainly dolomite marbles, in which were formed inclusions of olivine, pyroxene, or amphibole, and these were subsequently altered to serpentine. Other examples would seem to have been mashed and shattered serpentines, in the interstices of which calcite has been deposited by percolating waters.

7. *Anthracite* is a metamorphic coal, though it may perhaps have been formed in other ways also. When a bed of bituminous coal is intruded by a dyke, or sill, or other form of plutonic body, the heat changes the coal to an anthracite or to a natural coke. On a large scale, anthracite is found in intensely folded and compressed rocks, as in the basins of northeastern Pennsylvania. Traced west of the Appalachian Mountains, semibituminous coal is found in the middle of the state and in the western part, where the strata are almost horizontal, the coal is bituminous. A small amount of anthracite is found in folded and compressed strata of Wales and Belgium. A more intense metamorphism of carbonaceous deposits gives rise to *graphite* (or black lead), a semi-crystalline form of carbon, which is, however, rather a mineral than a rock.

II. Foliated Rocks

These rocks represent the most advanced stage of metamorphism and may have been derived from either sedimentary or igneous originals; it is not always possible to say which.

1. Gneiss is a coarsely foliated rock of widely comprehensive significance, for the different kinds correspond to some one of the plutonic groups in composition. Usually the light bands consist

of a mixture of quartz and feldspar and the dark bands are made up of parallel flakes of some ferro-magnesian mineral. The nomenclature of the varieties of gneiss is a double one: first, according to the nature of the dark mineral, such as *biotite gneiss, hornblende gneiss, augite gneiss*, and, secondly, the classification of C. H. Gordon, which uses the type of igneous rock to which the particular gneiss is most nearly allied. "Thus when we say granite gneiss, syenite gneiss, diorite gneiss, we use it to denote rocks having the composition indicated by the first word and the texture indicated by the second." (Pirsson.) The commonest variety is granite gneiss, with mica or hornblende as the dark mineral.

Most gneisses were generated by the violent compression of granite either before or after solidification. Some authorities deny that gneiss has ever been formed from sedimentary rocks, but the chemical composition of some specimens is quite unlike that of any igneous rock and others were plainly metamorphosed conglomerates, in which the original pebbles, crushed and flattened, are distinctly visible, especially on a weathered surface. Still another series of these rocks are of complex origin, granitic magmas being injected into metamorphosed sediments.

Gneisses are very widely distributed, occurring especially among the most ancient of known rocks, and they cover vast areas in the northern part of North America.

2. The Crystalline Schists have a much finer texture than gneiss, into which they often grade imperceptibly; they have diverse modes of origin from both igneous and sedimentary rocks. Slates, quartzites, impure sandstones, and limestones, as well as felsites, andesites, diabases, tuffs, etc., may all give rise to schists. The varieties are named from the most abundant ferro-magnesian mineral.

1. *Mica Schist*, the commonest of these rocks, has as the essential minerals quartz and mica, more generally muscovite, but biotite may be associated with muscovite, or be present by itself. Some feldspar is usually present also. By increase of feldspar and coarsening of texture, mica schist grades into gneiss and, on the other hand, by increase of quartz, into quartzite and sandstone. Through the phyllites, the mica schists are connected with the slates and, in another direction, by increase of lime they pass into argillaceous limestone. Mica schists, though essentially composed of quartz and mica, often have large and perfect crystals

of other minerals, especially garnet, but also staurolite, cyanite, epidote, hornblende, and others. Mica schists are very largely exposed in New England and along the eastern flank of the Appalachians.

2. *Hornblende Schist* consists of hornblende, with a varying proportion of feldspar and less quartz than does mica schist. These rocks are, for the most part, derived from the metamorphism of various basic igneous rocks, the augite being readily converted into hornblende by crushing. These schists occur extensively around Lake Superior.

The mica and hornblende schists are much the commonest and most abundant rocks of the group, but there are several others of less importance. *Talc* and *chlorite schists* are due to alteration, chiefly of the hornblende variety; *graphite schist* has that carbonaceous mineral distributed along the foliation planes.

An entirely different scheme of classification is that developed by Grubenmann, in which only the chemical composition of the original rocks before metamorphism is taken into account. From this point of view, the earth's crust is divided into three concentric shells: one near the surface, the second at medium depths, and the third very deep. Rocks of a given chemical composition yield metamorphic forms which differ in their minerals and texture in accordance with the depth of the shell in which the transformation took place. In this mode of classification the main divisions are made according to chemical composition, the subdivisions in accordance with the mineral components and texture of the rocks. This plan has proved to be a valuable conception, but it is more adapted to the laboratories of chemistry and petrology than to elementary instruction and therefore will not be elaborated here.

B. The Processes of Metamorphism

While much has been learned regarding metamorphism, more remains to learn, and there is therefore debate concerning many of its features. The difficulty lies in the fact that, aside from experiment, the processes cannot be observed, but must be inferred from the results and this impossibility always leaves open the way to differences of opinion. Of late years, opinion has undergone great changes concerning these problems and no one fancies that finality has been reached in any of them. Certain facts, however,

have found general acceptance and from these it is hoped that further progress in understanding may be made.

1. *Heat.* Of the causes of metamorphism the most indispensable is a high temperature, but differences of interpretation arise concerning the genesis and derivation of this temperature. When a body of igneous magma invades a rock, it heats the rock invaded and brings about the sort of change which is called *contact metamorphism,* but while heat is necessary to the change, it is seldom sufficient when acting alone.

Certain metamorphic rocks, such as quartzite and marble, have been successfully imitated with dry heat, though the production of marble requires pressure, to prevent the escape of CO_2 from the compound $CaCO_3$. Unless such escape is prevented, limestone is converted into quicklime ($CaCO_3 - CO_2 = CaO + CO_2$) as happens in every limekiln. If the gas is held in composition, the calcite crystallizes and marble results. No very high temperature is required. Bessemer "converters" are lined with gannister, a siliceous rock, and subjected to the temperature of molten steel, while an air blast is forced through the metal, to burn away the surplus carbon. When it is necessary to reline the converter, the gannister is found to be crystalline, without having melted. This artificial quartzite differs from most natural quartzites in not having the additional silica deposited in optical continuity around the original grains. The temperature of the molten metal is probably above that in ordinary contact metamorphism.

2. *Mineralizing Vapors.* Of the mineralizers water is the most abundant, and its effect is to lower the temperature of fusion and of the regenerating and recrystallizing of minerals. Superheated water, under great pressure, is able to attack the most refractory compounds and cause the crystallization of minerals that have never been crystallized by dry heat. Rocks which require 2500° F. to melt them in the dry way, will melt at 750° in the presence of water, whether as liquid or as vapor. Similarly water, or steam, will lower the temperature necessary for metamorphism. When a molten magma invades a series of rocks, the mere conductivity of the invaded rock would not carry the effect of dry heat far from the surface of contact, but the mineralizers, steam, fluorine, chlorine, boric acid and other active agents, penetrate the country rock to much greater distances. The distance of effective change will

depend upon the amount and kind of the mineralizer, the pressure they exert, and the porosity of the rock invaded.

A batholith which has a cover of no very great thickness will send out vapors, gases, and solutions that penetrate the country rock with transforming effects, with the principal effects upward through the overlying beds. Laterally, the distance reached varies greatly with the nature of the intruding magma; the quantity of mineralizing vapors and solutions which emanate from the plutonic body, the permeability of the country rock, are all factors in determining the amount of change and the distance to which it penetrates. It is customary to distinguish between hydrothermal and pneumatolytic action, the former caused by water under pressure and below the critical temperature and the latter the work of vapors and gases. The distinction is not, however, one of great importance, for aqueous solutions may be heated far beyond the critical temperature of water without vaporizing (Morey), and steam may hold solid substances in solution.

3. *Pressure* in the sense of static overburden, as distinguished from active dynamic compression, is equal in all directions and is necessary to prevent the escape of the mineralizing vapors and other gases. Limestone, to generate marble, must be heated under pressure.

4. *Compression.* By this is meant an active force, unequal in different directions, which folds, shears and mashes the rocks subjected to it. It is an unanswered question just what violent compression can accomplish in the way of metamorphism, or whether, indeed, it accomplishes anything. In conjunction with heat, moisture, vapors, and gases, it is very effective as a metamorphosing agent.

5. *Cementation* is the deposition of minerals from solution in the interstices of the rock which is undergoing metamorphism. Such solutions are hot and are derived from intruding magmas and are active agents of chemical change. When some of the minerals of the country rock are dissolved and carried away and their place taken by the deposition of the minerals emanating from the magma in solution, there is an actual replacement of one mineral by another. Such replacement is called *metasomatism*, a term which is now applied to the "*process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly different chemical composition may grow in the body of an old mineral or mineral aggregate.*" (Lindgren.)

6. *Injection* is the penetration of the country rock by magmatic material, and it is sometimes astonishing to see how the magma, which must be very thin, has permeated the intruded rock. The

Fig. 251. — Contact metamorphism in mica schist by a vein of pegmatite, about one-half natural size, Wells Island, St. Lawrence River, N. Y. (Photograph by J. R. Sandidge)

distinction between cementation and injection is not a very sharp or important one, for under magmatic conditions of temperature and pressure, water and magma are miscible in all proportions, so

that the distinction between fusion and solution becomes shadowy. Nevertheless, in their typical manifestations they are quite different, especially in the property of viscosity, a property in which there is great difference even among typical and unquestioned magmas. Sometimes a magma is injected into a rock so as to make a most intimate mixture of the two, much as a sponge soaks up water. In other instances and presumably with more viscous magmas, the injection forms many small sills, thin layers of country rock alternating with similar layers of the igneous intrusive. For

FIG. 252. — Mica schist with injected vein of pegmatite and development of pegmatite "eyes," Wells Island, N. Y. (Photograph by J. R. Sandidge)

this structure the French term, *lit par lit* (bed by bed), is somewhat unnecessarily employed, as the English phrase would suffice.

In attempting to classify the different types of metamorphism, great differences of opinion are immediately encountered as to certain aspects of the problems, while in others there is almost complete agreement, but there is still much confusion in the terminology used by different writers. One scheme is to divide all metamorphism into two classes: (1) *Thermal*, caused principally by heat, and (2) *Dynamic*, caused by compression and stress difference.

Nearly, but not quite, synonymous with this is the division into (1) *Contact*, or *Local*, the effect of intruding igneous magmas upon the rocks intruded, and (2) *Regional*, in which immense areas of rock, many thousands of square miles, have been transformed through recrystallization and the genesis of new minerals. Another scheme recognizes four types: (1) *Static* metamorphism, which operates near the surface of the ground, without stress and in the presence of small proportions of water. (2) *Dynamic* metamorphism, as defined above. The static and dynamic kinds are regional, contact metamorphism is local, though by the multiplication of intrusions, it may affect very wide areas. It is a matter of debate whether compression and stress, acting by themselves, are sufficient to produce metamorphism. (3) *Igneous* metamorphism (or *pyrometamorphism*) is the effect of intruding magma on the country rock and is practically the same as the contact class. (4) *Hydrothermal* metamorphism is the change caused in rocks by ascending hot waters. Igneous metamorphism may be local or regional and may or may not produce changes in composition, while the hydrothermal agency is local and involves chemical changes.

I. Contact Metamorphism

This is the change brought about by the action of intruding magmas, and the emanations from them, upon the invaded or country rock. Extrusive, or volcanic, flows have but little effect upon the rocks or soils over which they pass, because of the manner in which a lava stream speedily surrounds itself, top, bottom, and sides, with a cover of non-conducting scoriæ (see p. 89), and lava streams have been frequently observed to flow over the snow on the top of Ætna without melting it. Lavas thus generally produce but little visible change and often none at all. Bituminous coal may be baked into a natural coke, and clay "fired" into a hard red rock like brick, and limestone converted into quicklime, but even such slight changes are exceptional. Plutonic intrusions are much more effective, because they are presumably at a much higher temperature and retain their heat longer and there is no scoriaceous cover to separate the hot magma from the intruded rock. The highly heated emanations, solutions, vapors, and gases, cannot escape into the air, as they do from lavas, but are forced, under very high pressures, into the country rocks, extending, according to varying cir-

cumstances, from a few inches to two miles, which is apparently the maximum distance so far observed.

The rock invaded and metamorphosed may be of any kind, igneous, sedimentary, or already metamorphic, and the transforming effects may be very radical or surprisingly small. Indeed, it is often very difficult to imagine why the changes should be so insignificant. Probably the amount and character of the mineralizers is the most important factor in determining how extensive the

Fig. 253. — Granite intrusions parallel to gneiss, near Worcester, Mass. (Photograph by Keith, U. S. G. S.)

reconstructing effect shall be, and this is, no doubt, the reason that acid magmas are more effective than basic. Plutonic bodies which cut across the bedding planes, such as dykes, stocks, and batholiths, are more active agents of transformation than are those which, like sills and laccoliths, are conformable with the bedding planes. Most sills are basic and therefore have less of the mineralizers, and this, together with their relation of concordance with the strata, explains the smallness of the metamorphic effect which they so often produce. Laccoliths, too, though generally of more actively

mineralizing, acid magmas, often have very little effect upon the inclosing strata. Figures 5 and 12 exhibit the lower contact of the Palisades sill with Triassic shales, which have been but little altered by the heat. The nature of the rock which is invaded and metamorphosed is an important factor in determining the result; sediments which contain considerable proportions of alumina and lime are much more readily and profoundly changed, with the genesis of many more new minerals, than are the rocks composed of silica. Pure limestones form only white marble, except as other substances are forced into them by cementation, or injection, from the intruding magma. Most limestones, however, are more or less impure, because of the presence of clay, sand, iron compounds, etc., and such impure limestones may give rise to many new minerals, on contact metamorphism, independently of such extraneous substances as may be derived from the magma.

In a series of strata, in which different kinds of rock are found in the same vertical column and which has been traversed by a thick dyke, the effects of contact metamorphism may be conveniently studied. The temperatures involved are, generally speaking, not very high, because in accessible rocks the invading magma has passed through great masses of relatively cool country rocks and has lost much of its heat. According to Bowen the temperature of contact metamorphism is: "Very rarely and locally upward of 1200° [2192° F.]; occasionally and in restricted amount somewhat above 870° [1593° F.], but generally below 870°." In metasomatic contact metamorphism the effects are "transitional into those of thermal metamorphism and, occasionally, above 573° [1063° F.]. Usually below that temperature and graduating into replacement deposits of relatively low temperature."

Starting with the parts of strata which show no sign of effect from the heat and tracing them toward the dyke, a sandstone may be traced into a quartzite, which may be merely a crystallization of the sand, or may show the addition of a large amount of crystalline silica deposited around the original sand grains and in optical continuity with them. The additional silica must have been carried in by solutions from the magma. If in the original sandstone there is any considerable percentage of clay, or lime, or undecomposed particles of feldspar, mica, etc., or both, many new minerals may be generated by recomposition and recrystallization in the contact zone, such as muscovite, chlorite, epidote, magnetite, etc.

The crystals are usually of microscopic size, but they change the normal white, yellowish, or pale gray color of quartzite into a dark shade of green, blue, purple, or even black. The most important of the regenerated minerals is muscovite; as this mica increases in amount, it gives the rock a cleavage through the flakes and eventually the quartzite may pass imperceptibly into mica schist.

Shales, mudstones, and clay rocks generally undergo more radical changes and are usually divisible into more or less distinct zones. In the outermost zone the rock has undergone no visible change; in the intermediate zone, the rock has become a dense, hard slate, spotted with biotite and other dark minerals. The spotted slate changes to phyllite (*q.v.*) and this again to a mica schist. Near the intruding body, the rock becomes a *hornfels*, a German term which is widely used, because the English equivalent, *hornstone*, though occasionally used in the sense of hornfels, is properly one of the names of flint, or chert. Hornfels is a dense rock, in which the granules are too small to see, except with the microscope; it breaks with a conchoidal fracture and is so dark in color that it looks like basalt and resembles it in structure, for all signs of stratification have been obliterated.

Limestone, when pure, yields a white marble, provided the metamorphism takes place at a depth where the pressure of the overlying rocks will prevent the escape of CO_2. Coloring matter, in the shape of organic substances, or iron compounds, give the black, gray, yellow, red, and brown shades, as already explained. Most limestones contain varying proportions of clay and sand, which sometimes exceed 50 per cent in amount, and in dolomites and magnesian limestones the magnesia supplies material for additional combinations. Aided by the hot vapors and gases derived from the intruding magma, many new minerals are generated; the silica takes the place of CO_2, the carbonates becoming silicates. Wollastonite ($CaSiO_3$), pyroxene, garnet, and anorthite are very common as contact minerals and usually they are scattered through the marble, but they may replace the latter entirely in the contact zone. Several contact minerals depend for some of their constituents upon the mineralizing vapors, such as boron and fluorine, for instance, which are not found in a normal limestone, whence come such minerals as tourmaline, mica, topaz, epidote, etc., etc. This effect of the vapors is called *pneumatolytic*, and according to their abundance and high temperature, the avenues of escape of the

vapors, and other varying factors, the masses of contact minerals differ in size. In some instances, all the original strata are replaced by masses of new minerals. These masses are not continuous and uniform but in disconnected bodies, large and small, and especially in and around fissures, through which the vapors passed. Extreme metamorphism of impure limestone may result in a mica schist, which may thus be formed from the arenaceous, argillaceous, and calcareous sediments.

II. Dynamic Metamorphism

By this term is meant the reconstruction and recrystallization of the rock-forming minerals which are effected by the violent compression and plication of rocks. Heat is, of course, essential in all kinds of metamorphism, but in the dynamic kind, the heat is supposed to be mechanically generated by friction, and the necessary water is presumed to be that contained in all sedimentary rocks. This is a controversial subject, as to which the most widely different opinions are held by various writers on these subjects. The main matter of debate is whether any amount of compression and mashing, even though in the presence of water, will generate temperatures sufficient for metamorphism. No one questions the importance of compression, shearing, and mashing in metamorphism on a great scale; the doubt concerns the effectiveness of it when acting alone and without the coöperation of the mineralizers.

For example, there is the remarkable contrast between the folded Palæozoic rocks of the Pennsylvania Appalachians and those of southern and western New England. The eastern Appalachians in Pennsylvania are very closely folded and crumpled, indicating a great shortening of the earth's crust along that belt. The belt has been most profoundly denuded and the strata now exposed had formerly been buried to a depth calculated at six miles, which, when invaded by the earth's internal heat, must have had a temperature approximating 600° F. Notwithstanding all this, those strata show very little sign of metamorphism, a fact which, to all appearance, is because of the absence of igneous intrusions. The shales have been converted into cleaved slates and some sandstones into quartzites, but the limestones have not been converted into marble, not to mention the formation of mica schists. In New England the metamorphism is complete and the difference between the two areas has been ascribed to great batholiths and the

emanations from them. Barrell was of the opinion "that the regional metamorphism is intimately related to the batholithic intrusion. . . . This conclusion applies to all southern New England, and apparently much the same relationship between intrusion and metamorphism existed in the Laurentian invasion."

Harker has reached essentially the same conclusion: "There can be, I think, no doubt that the solvent medium which is essential to metamorphism is to be ascribed *ultimately* to a magmatic source. Since, however, metamorphism can evidently go on far from any igneous intrusion, we are to conceive a pervading medium, doubtless of extreme tenuity in general but attaining a greater concentration in the neighborhood of newly-intruded igneous rocks." The difference between Barrell and Harker is that the latter would admit that "metamorphism can go on far from any igneous intrusion," while the former would have made no such admission.

Professor Daly "has observed a nearly complete absence of recrystallization in the Lower Cretaceous arkose and shale of the Pasayton series in British Columbia. Yet those beds were formerly beneath younger Cretaceous sediments probably more than 8,000 meters thick." Much the same thing is true in northern California, yet Daly defines dynamic metamorphism as that "which is induced in rocks because of their deformation, the crustal movement being of the orogenic type."

Slaty cleavage is of course due to compression, and foliation on a large scale would seem to be dependent upon it, but the necessary degree of heat and the "solvent medium" would seem not to be explained by compression and shearing alone.

III. Regional Metamorphism

As usually employed, this term is almost equivalent to dynamic metamorphism, and as it seems unnecessary to have two terms for the same thing, it would be well to adopt the suggestion of Geikie and define regional metamorphism as the kind which affects large areas, without specifying any particular agent as having wrought the change. The northern part of the North American continent, including Greenland, is an area, some millions of square miles in extent, of metamorphic rocks, called the *Canadian Shield*, which everywhere shows evidence of extreme compression. It was natural to infer that metamorphism on so vast a scale must be

independent of igneous intrusions, especially so long as it was believed that the banded granitic gneisses were of sedimentary origin. Now that most of these rocks have been definitely transferred to the igneous class, the problem assumes an entirely different aspect. These "primary gneisses" are foliated granites, compression of the still more or less fluid magma producing a flow structure, causing the earlier-formed minerals, especially black mica, to form parallel bands. As Pirsson and Knopf say: "Such gneisses are not metamorphic rocks at all."

The probable conclusion is, then, that while local or purely contact metamorphism is due entirely to igneous intrusions, regional metamorphism requires the coöperation of diastrophic compression and shearing together with the high temperatures and emanations of magmatic intrusions.

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CHAPTER XXIII

ORE DEPOSITS

So great is the economic importance of these deposits that they have long been the object of close study, but there still remains much concerning their genesis that is doubtful and obscure. The term *ore* is commercial rather than geological, for it means a natural mineral substance from which some metal may be profitably extracted, and its value is determined not only by its content of metal, but also by the cost of working, transportation, etc. What is an ore in one place may not be so in another, and as processes are cheapened, deposits that were of no value are converted into ores. The difference, however, is one of degree and depends upon the quantity of the metal present; a lean, low-grade ore is to be explained in the same manner as a rich and high-grade one.

The problem of ore deposits is that of concentration, for most of the economically valuable metals are very widely disseminated, or are of universal occurrence, but in minute quantities. Like everything else on and near the surface of the earth, perhaps even the ocean and the atmosphere, metals are believed to have been ultimately derived from igneous magmas, but they may have undergone many transformations, concentrations and dispersals, before reaching the condition in which they are now found. Many ores, on the other hand, are still associated with igneous rocks and their magmatic origin is clear. Several classifications of ore deposits have been suggested, but to be consistent with the methods now dominant in geology and geography, a genetic scheme must be adopted, that is, an arrangement in accordance with the mode of origin. The classification here employed is the one proposed by Professor W. Lindgren.

Ore Shoots. Commercial ore seldom makes up the whole of a mineral body and often forms but a small part of it. The part so concentrated that it can be profitably worked is called an ore shoot. In metalliferous veins the ore shoots, which are sheet-like

or tabular bodies, appear as more or less continuous areas. The remainder of the vein is composed of barren minerals which are called *gangue*. The commonest gangue minerals are quartz, calcite, and barite (heavy spar). Ore shoots are predominantly lenticular in shape and nearly always diminish and die away in depth and along the strike. Ore shoots are *primary*, when formed together with the gangue, or inclosing rock, other than the country rock, which the shoots invade, or *secondary*, when formed or concentrated by secondary processes of enrichment, usually by surface waters.

PRIMARY ORE SHOOTS

A. Ores Due to Magmatic Differentiation

1. Oxides and Native Metals. As a magma consolidates slowly, fractional crystallization, aided by gravity and perhaps other agencies as well, frequently causes it to separate into parts of different mineral and chemical composition. Sometimes the magma carries so large a proportion of useful metallic compounds that the segregation of them forms workable bodies of ore, and some of these are very valuable; but, as a class, they are not nearly so important as the deposits made from solution in water. There are but few of these ore minerals in the igneous rocks, and they are of a simple composition, mostly oxides and sulphides and some native metals. The most abundant of these minerals are magnetite (Fe_3O_4); ilmenite or titanium-bearing magnetite ($FeTiO_3$); cassiterite (SnO_2), oxide of tin; pyrrhotite (Fe_7S_8) and pyrite (FeS_2), iron sulphides; pentlandite (FeNiS), iron and nickel sulphide; chalcopyrite (FeCuS), iron and copper sulphide; molybdenite (MoS), molybdenum sulphide; chromite ($FeCr_2O_4$), chromium and ferrous iron oxide. The presence of iron in nearly all of these minerals is a noteworthy fact. "The characteristic feature of a deposit of this class is that it is a part of a body of igneous rock; the crystals of its minerals formed in the magma solution from which the rock crystallized, or in one similar to it. The associated gangue minerals are those which make up igneous rocks." (Lindgren.) Ore deposits due to magmatic differentiation are formed at very high temperatures and under great pressure.

1. *Ilmenite*, or titaniferous iron ore, with magnetite, is contained in almost all basic rocks and is sometimes segregated in very large

masses contained in gabbro, or anorthosite. Large deposits are found in the Adirondacks and in many other places; in eastern Wyoming, for example, a dyke of ilmenite, with a maximum thickness of 300 feet, cuts through anorthosite. In the Transvaal, South Africa, is a most remarkable deposit of strongly magnetic, titaniferous iron ore, which forms a broad belt between extensive bodies of gabbro (norite) on the one side and red granite on the other. Longitudinally this belt extends for tens of miles and is evidently segregated from the gabbro magma. Ilmenite has not been largely exploited as a source of iron because of the difficulty of smelting it.

2. *Magnetite*, differentiating from magma, is associated with syenite, as are the ores of northern Sweden, the largest deposit of magnetite yet discovered. In 1929, 9,000,000 metric tons of ore were mined. Magnetites derived from syenite are found in the eastern Adirondacks and yield one to two million tons of ore per year. Similar deposits are known elsewhere, as in the Ural Mountains of Russia, but the greatest sources of iron ore are deposits which have been formed by subsequent concentration.

3. *Chromite* is a segregation in peridotite and in the serpentine which has been derived from the alteration of that rock. As forming a valuable alloy-steel and serving the same purposes as nickel, the metal chromium, all of which is smelted from chromite, is coming into wider and wider uses. The ore is very extensively distributed in Canada and the United States and was mined on a large scale in Asia Minor and the island of New Caledonia, but the extraordinary deposits in Rhodesia are now supplying nearly all the demand. The outcrops of chromite run for forty miles continuously and occur in parallel, flat sheets in the serpentine of the Great Dyke.

4. *Platinum Metals*. Platinum has hitherto been chiefly derived from placers (see p. 534) in the Ural Mountains of Russia, but has been discovered in that mineral wonderland, South Africa, where it occurs in the basic igneous rocks of the Transvaal and southern Rhodesia. The metal is found in association with palladium, osmium, iridium, and others of the group. Some of the chromite bands in serpentine of the same region carry platinum.

2. Sulphides. It has been proved that a few metallic sulphides may crystallize out from a magma, but only a few of the metals occur in this manner: iron, copper, molybdenum, zinc, and nickel.

Some of the sulphide deposits are basic rocks which carry an unusual quantity of pyrrhotite, chalcopyrite, pentlandite; while others again are found in igneous rocks that have been metamorphosed dynamically, though the sulphides are primary.

Nickel. Most of this metal now produced in the world is derived from Sudbury, Ontario. In a synclinal trough thirty-six miles long by sixteen miles wide, there is an intrusive sheet of igneous rock that is much differentiated, presumably by fractional crystallization. Below, the sheet is a norite, or hypersthene gabbro, and it grades upward into a granite. The ore-minerals are pyrrhotite, pentlandite, and chalcopyrite, with a little magnetite and pyrite, sphalerite (zinc sulphide, ZnS), and the arsenide of platinum.

Three different explanations of the Sudbury ores have been suggested: first, that they have been formed by segregation from the magma; secondly, molten sulphides have been subsequently injected; and thirdly, that they have been deposited from solution in hot waters. "That the nickel ores are genetically connected with the norite admits of no doubt." (Lindgren.)

B. Ores in Pegmatite Dykes

As was described on p. 51, a consolidating magma from which the mineralizers and other volatile constituents are unable to escape becomes more and more a high-temperature aqueous solution in which crystals are able to grow to extraordinary size and perfection of form. The rocks so formed are called pegmatites and they are associated as dykes, sheets, and irregular masses with the various plutonic bodies from which they were derived. Most pegmatites are granitic in composition, but they also occur of intermediate and basic composition. As previously told (p. 58), pegmatites contain many rare minerals, including gems, which are not known to occur elsewhere. In the acid pegmatites the characteristic mineralizers are fluorine and boron and in the basic dykes phosphorus and chlorine. Pegmatites consolidate at relatively low temperatures, 565° C. (1050° F.), but under very high pressure.

Of the ores found in acid pegmatites, that of tin, cassiterite, is much the most important. Wolframite is usually associated with the tin ores in pegmatites, but most of the output of tungsten is derived from mineral veins.

C. Ores Due to Contact Metamorphism

In Chapter XXII the metamorphic and metasomatic, or replacement, effects of intruding magmas were outlined, and among these the most important economically is the deposition of ore bodies in the contact zone. The mineralizing vapors, carrying various metallic oxides and sulphides in solution, force their way into the country-rock, developing new minerals and depositing ores, chiefly by replacement. Contact ore-bodies are seldom in sandstones or shales, almost always in limestones, which "are easily permeable and appear to soak up the solution like a sponge." (Lindgren.) The effect produced depends upon the degree of concentration of the solutions; when these are very dilute, no great changes take place, but with stronger solutions the limestone is replaced by a mass of ore and gangue minerals. The temperature is high at the contact (as much as 1500° C.), diminishing rapidly in the country rock.

Pyrrhotite, chalcopyrite, sphalerite, and molybdenite are the usual sulphides, magnetite and specularite the commonest oxides. The gangue minerals are silicates of calcium, magnesium, iron, and aluminium, such as garnet, epidote, diopside; quartz is seldom present in any considerable quantity, but large crystals of calcite are abundant.

1. *Magnetite* deposits are the most frequent of the contact-metamorphic ores, but the bodies are usually small. At Cornwall, Pa., is a large body of magnetite which has been extensively mined and chalcopyrite is also taken out. A diabase sill is in contact with Triassic shales and Palæozoic calcareous shales; the former display the baking effects of the hot intrusive magma, while the latter have been largely replaced by magnetite and tremolite, with other minerals in less proportion.

2. *Chalcopyrite*, the sulphide of copper and iron ($CuFeS_2$), is one of the most important of productive ores, especially in Mexico, New Mexico, and Arizona, Australia, Japan, and Korea. In the southwestern United States the ores are generated along the contact between intrusive quartz monzonite and limestone. In smaller quantities sulphides of other metals are deposited, iron, zinc, molybdenum; magnetite is often present as well. There is little gold or silver.

3. *Sphalerite and Galena.* These sulphides of zinc and lead respectively occur in small quantities in most of the ore bodies formed

by contact metamorphism, but they are seldom the principal ores. The Magdalena Mountains of New Mexico are made up of fault-blocks of limestone, cut by granite dykes, and along the contact zone there are large bodies of zinc sulphide, with some of lead and copper. In eastern Mexico the limestones have been invaded by many small intrusive bodies, which have developed sulphide ores along the contact. For the most part, these ores are of copper, but lead predominates in some of them.

4. *Gold and Silver*. Traces of gold and a little silver are found in most sulphide bodies formed by contact metamorphism, but it rarely happens that these metals supply the principal value of the ores. In Montana and British Columbia Carboniferous limestones have been invaded by sheets of gabbro and diorite, which are not exactly concordant with the bedding planes of the stratified rocks. The most abundant of the sulphides is arseno-pyrite, in which the gold is contained; the pure arseno-pyrite may carry as much as $350 in gold per ton. There is very little silver, and but traces of platinum and nickel are found.

5. *Scheelite*, tungstate of calcium ($CaWO_4$), occurs in California and Nevada along contacts between granite and limestone, and in quantities that make these deposits an economically important source of the metal tungsten. There are metamorphic deposits of ore which have no clear relation to contact with intrusive igneous rocks and yet have the same association of minerals, which points to their formation by similar agencies. It may be that the plutonic intrusive is vertically beneath the ore body and concealed by a few hundred or a few thousand feet of rock. An especially interesting ore deposit is at Ducktown, in the Appalachian Mountains of eastern Tennessee, which has been worked for copper since 1848 and still produces 9,000 tons of the metal annually. The ore is in intensely folded, compressed arkose; sediments which have been metamorphosed into crystalline schists, and is a coarsely crystalline mass of the sulphides of iron, copper, zinc, and lead, with iron oxide and a long list of silicates. All these would appear to be emanations from an igneous intrusive, but if so, the source is not known.

Another remarkable and much-debated ore body is the great deposit of zinc and manganese minerals at Franklin Furnace in northern New Jersey. There are two ore bodies, one at Mine Hill and the other, three miles away, at Stirling Hill, and they are in a

coarsely crystalline Pre-Cambrian limestone, with gneiss of igneous origin adjoining the limestone. The ore is made up principally of franklinite, a complex oxide of iron, manganese, and zinc [$(FeMnZn)(FeMn)_2O_3$] but with a large proportion of willemite, silicate of zinc (Zn_2SiO_4), and a small quantity of zincite (ZnO). Associated with the ore is a host of rare minerals, 100 different kinds so far known, many of which are not known anywhere else in the world. Most of these are attributed to emanations from the pegmatite dykes which cut across the ore body. A remarkable feature of these deposits is the absence of sulphides, which are found only in younger veins that intersect the ore body.

No generally acceptable explanation of these extraordinary deposits has been propounded, though many theories of their origin have been suggested. Professor Lindgren says of them: "It is certain that the texture of the ore and the universal rounding or corroding of the ore minerals point distinctly to igneous metasomatic action. The abundance of the spinel minerals is indicative of high temperature."

D. Metalliferous Veins, or Lodes

The crevices and fissures which traverse hard rocks are frequently filled by the deposition of crystalline substances and are called *mineral veins*. They vary greatly in dimensions, from a few inches to many miles in length. Minute veins are filled by solution and redeposition of material derived from the walls, such as the veins of crystallized calcite in limestones. *Great fissure veins*, on the other hand, which may run for many miles and extend to depths beyond the reach of mining, are characterized by regular walls, fairly constant width, and by definite direction of dip and strike. Such veins are usually very distinctly marked off from the walls of country rock and may be either simple, or banded, with the bands parallel to the vein-walls. In a simple vein the mineral filling is either deposited irregularly, with no definite arrangement, or in a solid, homogeneous mass, while the banded structure is produced in several different ways. One of the commonest of these ways is by the deposition of minerals on the walls of an open fissure, the more perfect ends of the crystals projecting toward the middle of the vein, and the bands are usually arranged in symmetrical pairs from the walls inward.

In many veins the symmetrical arrangement is departed from

because a fissure may be reopened and renewed deposition follow, the older vein forming one wall of the newer one. The parallel bands may all be of the same mineral, or each symmetrical pair may be different from the others. A zone of shattered fault rock may be converted into a mineral vein, which then will be highly complex, branching and anastomosing around the broken pieces of country rock. The nature of this wall rock itself often determines whether a vein shall be simple or complex, and the same vein may be simple in one part of its course, or complex in another, as the

FIG. 254. — Pegmatite veinlet in diabase, faulted and offset by later datolite-calcite veinlet; about one-half natural size, Goose Creek, Va.

wall or country rock changes from point to point vertically or horizontally along the strike of the vein. Before the deposition of the mineral contents, the fissure or fault was open in part of its course, full of rock fragments in another, yet with abundant interspaces through which the aqueous solutions, mostly hot, could circulate freely.

Still another class of veins comprises those of *replacement*, in which the circulating waters have gradually substituted one mineral for another. A replacement vein is apt not to have sharply defined walls, for the new deposits impregnate the country rock and fade away into it, especially if that rock is a limestone.

Metalliferous Veins are mineral veins which contain native metals or ores in economically important quantities; the most frequent gangue minerals are quartz, calcite, and barite (heavy spar, $BaSO_4$). They are deposited by ascending hot waters, which are of uncertain origin, whether vadose or juvenile, or partly one and partly the other. Whatever the derivation of the waters, they carry in solution emanations from magmatic bodies and deposit them in fissures under differing conditions of temperature and pressure. The scheme of classification of the metalliferous veins here employed is that propounded by Professor Lindgren in 1911, but the order is reversed, so as to fit the arrangement of topics used in this chapter. The division is into three groups, which are characterized by the conditions of temperature and pressure under which the deposit was made: 1. Hypothermal deposits, made under great pressure and at high temperatures, 300° C. to 500° C., and therefore at great depths. 2. Mesothermal deposits, made at intermediate depths and temperatures, 200° C. to 300° C., but still under high pressure. 3. Epithermal deposits, made near the surface under moderate pressures and at temperatures up to 200° C.

1. **Hypothermal Deposits** are found in or near plutonic bodies which have been exposed by denudation, though in certain rare instances conditions of high temperatures and pressures may be brought about near the surface. Gangue minerals, such as quartz, pyroxene, amphibole, mica, tourmaline, and feldspar, are of the high temperature kinds. Gold, copper, iron, tin, tungsten, and arsenic occur much more frequently in the hypothermal veins than do silver, lead, zinc, or antimony.

1. *Tin.* Cassiterite veins form a distinct group in which the ores cassiterite, molybdenite, arsenopyrite, wolframite, and bismuth are very commonly associated, while the sulphides of iron, copper, lead, and zinc are much less frequent. Quartz is always the chief gangue mineral and there are also lepidolite, fluorite, topaz, tourmaline, and apatite. Cassiterite is the most important ore of tin, but stannite, the sulphide of copper, iron, and tin (Cu_2FeSnS_4) is important in Bolivia. Cassiterite veins are associated with granite; the stannite silver veins in Bolivia are connected with bodies of quartz monzonite, and the tin of Japan is associated with diorite.

2. *Tungsten.* Wolframite is often found with cassiterite, but there are many veins in western North America and in Argentina

and Bolivia in which tungsten is the principal metal. The most prolific mines are those of Burma, which produce nearly one-third of the world supply.

3. *Gold-Quartz.* Hypothermal gold veins are found in many regions in Pre-Cambrian and the older Palæozoic rocks. There is a belt of such veins in the southern Appalachians from Maryland to Alabama, which have been successfuly mined. Quartz is the principal gangue mineral, but there is a long list of others, such as calcite, garnet, feldspar, tourmaline, pyrite, etc. These deep-seated gold veins are frequent in the Canadian provinces of Ontario and Quebec, in various western states, especially South Dakota and New Mexico, in Europe, South America, South Africa, and India. There are many other gold-quartz veins which were formed at higher levels and lower temperatures and pressures, or at later periods of geological time.

4. *Copper.* In many hypothermal veins is found the association of chalcopyrite with tourmaline and many other minerals in smaller quantities, the oxides and sulphides of iron, molybdenum, and tungsten, mica, fluorite, and quartz. Such deposits, which are widely distributed through the world, are sometimes in fissure veins, sometimes in the shattered zones of fault rock. The country rock is subject to extreme metasomatism and tourmaline is formed to considerable distances within the walls. Tourmaline-copper veins are frequent in Chile; in the Andes, at a height of 8,000 feet, southeast of Santiago is the Teniente, or Braden, deposit, which Lindgren calls "the most prominent representative of this type in the world." Smaller deposits of the same type are found in the Cordillera of the United States. A very exceptional series of veins is in the great Cobar district in New South Wales, Australia. These are replacement veins cutting lower Palæozoic sandstones and slates in a much-denuded desert range of mountains; the vein walls are not well defined, for the ore grades into the country rock. The ores are sulphides of iron and copper with some gold and silver; the gangue is quartz and other minerals. Though these veins must have been filled at great depths and high temperatures, no intrusive rocks are known for a long distance, but what plutonic bodies may be underneath them has not yet been ascertained.

5. *Lead-Silver-Zinc.* Lead and zinc sulphides are usually formed at lower temperatures than obtained in the hypothermal

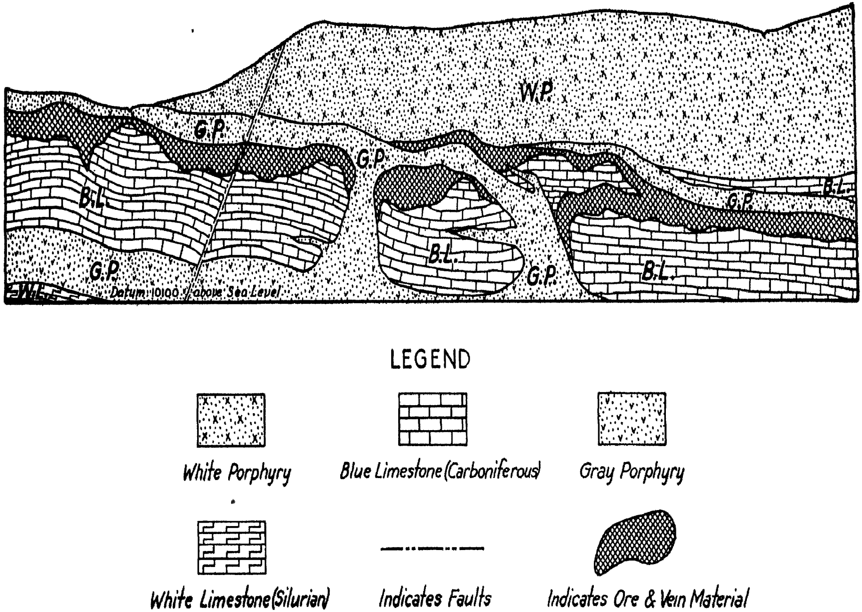

FIG. 255.—Longitudinal section of Stone ore-shoot, Iron Hill, Leadville, Col. (From A. A. Blow, modified by omission of artificial features)

zone, but some very productive high-temperature veins have been found in Mexico, New Mexico, and Montana, British Columbia and, above all, at the famous Broken Hill in New South Wales. Some of these veins have tourmaline in the gangue, as in the veins connected with the Boulder batholith in Montana; others have garnet, mica, and other high-temperature minerals, as at Broken Hill, in Australia, in the Kootenay district of British Columbia, and at Hatchita, New Mexico, and at several places in Mexico.

2. **Mesothermal Deposits** are those intermediate in depth of original formation, in temperature, and pressure; they include deposits in a shell approximately from 4,000 to 12,000 feet below the surface as it was when the veins were filled. Denudation has in all cases cut deeply into the ancient surface. Of course, a given temperature and pressure were not always at the same depth below the surface, depending largely upon the level to which the intruding igneous body had risen. The most frequent ores in veins of this class are sulphides and arsenides of silver, copper, lead, zinc, and native gold. Quartz is the principal gangue mineral, calcite and barite are common, but not the high-temperature minerals such as the amphiboles and pyroxenes and garnets, tourmaline, and topaz. The vein fillings are believed to be deposited from hot aqueous solutions, or *hydrothermal* action, which has also produced more or less extensive metasomatic or replacement effects in the country rock, and many ore deposits are regarded as due to replacement rather than to deposition in an open fissure. "The mesothermal deposits are probably largely derived from differentiation in congealing batholithic masses." (Lindgren.)

1. *Gold-Quartz Veins.* The association of gold and quartz is proverbial. Such veins have a wide vertical range, but the most important of them belong to the mesothermal class, such as those of the western Cordillera of North America and of eastern Australia. The Sierra Nevada Mountains of California are the seat of perhaps the most famous of the gold-quartz veins. The gold belt is on the western slope and in the foothills of the range and extends, with some interruptions, through the whole length of the state, from south to north. In Oregon it passes beneath newer rocks and is lost to sight. The greater part of the Sierra consists of an immense batholith of granodiorite and similar igneous rocks, which invade intensely compressed, folded, and metamorphosed sediments of Palæozoic and Mesozoic age, with

Palæozoic lavas and a vast accumulation of Jurassic lavas and tuffs. Smaller intrusions of gabbro, diorite, and granodiorite are referred to the Cretaceous period. The veins are most numerous near the smaller intrusions and cut rocks of any kind. In the Rocky Mountains from Colorado to Alaska are gold veins somewhat later in geological date than the California veins and differing from the latter in certain details, such as in having a larger proportion of sulphides and more silver, but they are essentially the same. In Victoria, New South Wales, and Queensland, folded strata of Palæozoic date are invaded by batholiths, which are assigned to the Devonian period. The whole region has been profoundly eroded, and it is estimated that in Victoria 3,000 feet of rock have been removed by denudation. The metallic sulphides occur in small proportions, and the gold veins are very much as in western North America. In the Rocky Mountain region are large bodies of gold and silver ores produced by replacement in limestones that have been intruded by plutonic bodies, and in the igneous rocks themselves are auriferous veins of replacement.

2. *Silver-Lead Veins*, in great variety of mineral content and association of ores, are found in the Cordilleran region. The gangue is principally of calcite and the carbonates of magnesium and iron. Great bodies of silver ore in these regions are due to replacements, especially in limestone. The ores are chiefly silver-bearing sulphides of lead (galena) and zinc (sphalerite). At Leadville, Colorado, was a famous deposit of silver-bearing carbonate, due to the oxidation and carbonation of the sulphide. Mexico has been a great producer of silver ever since the Spanish Conquest and the deposits are frequently horizontal replacement pipes, rather than veins, in the thick mass of lower Cretaceous limestones and associated with intrusive bodies. There are two principal classes of ore; first, pyrite containing silver and a little associated lead and zinc, and secondly, argentiferous galena with pyrite and sphalerite. There is much difficulty in explaining the mode of formation of these deposits, but there seems to be no doubt of their origin from the igneous intrusives. In Ontario, there is a celebrated deposit of silver ore in the cobalt-nickel veins of the Cobalt district, which in production of silver is second only to the great Mexican mines. The rocks of the mining district are of Pre-Cambrian date and are sedimentary, intruded by a very thick sill of diabase, with which the veins are connected. The

silver is often in sheets along the walls of the veins; one such sheet weighs 1,640 pounds.

3. *Copper Veins* of mesothermal origin are common, but few of them are of great value, unless they carry paying quantities of gold or silver. The most important of the copper veins are the pyrite-enargite, sulphide of copper and arsenic class in the Cordillera of North and South America. Argentina, Chile, and Peru have very productive mines of this type and the deposits at Butte, Montana, still yield a large production.

4. *Pyrite Replacement Deposits* include ore bodies of very different origin; some are associated with high-temperature minerals, such as amphibole, pyroxene, tourmaline, and garnet, others with minerals formed at lower temperatures, calcite, barite, and quartz. In northern California (Shasta County), in an intruded body of porphyry, are very large irregular masses of pyrite, carrying about three per cent of copper and small quantities of gold and silver. The pyrite is a replacement of the porphyry in sheared and broken zones.

The Rio Tinto copper deposits in southern Spain, still among the most productive in the world, have been worked since the third century, B.C. The ores are almost massive pyrite, with a little copper sulphide, and their mode of origin has long been discussed, with varying explanations. The best established conclusion would seem to be that they are replacements in sheared zones and along porphyry-schist contacts by hot aqueous solutions. Similar pyrite-copper deposits are found, among other localities, at Mount Lyell, in Tasmania, and in the Harz Mountains in Germany. The latter have been worked since the tenth century, at least, but there is no general agreement as to the origin of the ores.

3. **Epithermal Deposits,** like the hypothermal and mesothermal, are derived from igneous magmas by ascending hot waters and deposited in fissure veins, mostly in lava flows of Tertiary age. The lavas are nearly always of the intermediate and acid kinds, seldom basalts, and they are, for the most part, of circum-Pacific distribution, though also occurring in Hungary and Transylvania. Veins of this type occur in New Zealand, the East Indies, Japan, and, above all, in the Cordilleran region of the Americas, where are found the famous "bonanzas" (a Spanish word which means success) to which so much of the romance of Colorado, Nevada, and California is due. Much of the annual production of gold,

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silver, and mercury is derived from these epithermal veins, and though silver often occurs by itself, gold and silver usually are found together. Copper is rare, but the sulphides of lead and zinc sometimes occur in quantity. Large pyrite deposits are absent, as they are confined to deep seated levels.

The principal gangue mineral is quartz, but calcite, dolomite, and fluorite are sometimes prevalent. The fact that these metalliferous veins occur in lavas is not regarded as significant by most students of the subject. Professor Lindgren says of them: "The deposits have nothing to do with the superficial volcanic phenomena, though some authors seem to think so. The solutions were truly of deep-seated origin, but their load was precipitated within about 3,000 feet of the surface."

The same author, while saying that a rigid classification of the epithermal deposits is difficult, recognizes ten more or less distinct types.

1. *Cinnabar*, the sulphide (HgS), is the only important source of mercury, and the economically important deposits are nearly always in regions of earlier or later volcanic activity, following the Tertiary and Quaternary lava flows. The Coast Range, of California, has a belt of mercury ores which formerly yielded large amounts of the metal, but no longer does so. Cinnabar deposits are very superficial and seldom extend below 1,000 feet. They are very widely extended around the Pacific, but nearly all of the world's supply comes from Idria, in Carniola, which is now a part of Italy, and Almaden in Spain.

2. *Gold-Quartz*. These veins differ from the gold-quartz veins of the mesothermal class in that they intersect lava flows of late geological date, and they are found in different kinds of extrusive rocks, rhyolite, andesite, dacite, etc. In Hungary, Rumania, New Zealand, Mexico, and the Cordilleran region of the United States veins of this type have yielded a large amount of gold. Some of the veins, as at Tonopah, Nevada, and the famous Comstock Lode, in the same state, carry large amounts of silver sulphide, argentite, associated with sulphides of other metals, lead, zinc, iron, and copper. Quartz and calcite are the gangue minerals.

3. *Gold Telluride*. A remarkable and well-known group of mines, the Cripple Creek district of Colorado, is in the pipe or neck of a Tertiary volcano, with a diameter of two or three miles, which has cut its way upward through Pre-Cambrian granite. The

volcanic chimney is filled chiefly with tuffs and breccias, cut by later dykes of basic rocks, and the veins were apparently formed soon after these intrusions, and irregular bodies of ore, due to replacement, are found in the granite walls of the volcanic pipe, near the contact. The valuable ore-mineral is a telluride of gold ($AuTe_2$) with small quantities of sulphides of iron, zinc, copper, antimony, etc. The gangue is chiefly quartz, but has also considerable proportions of dolomite and fluorite.

4. *Veins of Other Metals.* Ores of the base metals are not common among the epithermal class in such quantity as to be mined chiefly for those metals; sulphides of lead, zinc, and copper do occur quite widely, but the principal values are in gold and silver. Replacement deposits in limestone may be rich in galena. The San Juan Mountains in Colorado are largely made up of volcanic rocks, lavas, tuffs, and breccias, which were erupted at intervals during the whole Tertiary period and piled up to a thickness of many thousand feet. Since volcanic action ceased, denudation has carved the volcanic mass into extremely rugged mountains and has cut deep into the lavas, exposing a great number of metalliferous veins. There are large quantities of the sulphides of lead, zinc, and copper, but gold and silver give the chief value; the gangue is mainly quartz, but barite, fluorite, and manganese minerals are frequent.

5. *Copper and Zeolites in Lavas.* Native copper and its oxides, in association with zeolites (see p. 38), are frequently found in basic lavas, filling the vesicles and gas holes in the rock, though sometimes in replacement of it. These copper-bearing lavas are of world-wide distribution, but in only a few places are the ores rich enough to be exploited. Copper is disseminated through most, if not all, basic rocks, supposedly as a silicate in volcanic rocks and as a sulphide in intrusives. Concentration is due to hot waters. "Generally, however, the concentration in basic flows to valuable deposits can be designated as an eruptive after effect, which occurred soon after the eruption." (Lindgren.) The temperatures indicated are in the neighborhood of 300° C.

The most extensive and valuable of known copper deposits of this type are found in the northern peninsula of Michigan, along the shore of Lake Superior. There, in a vast syncline, is an immensely thick series of lava flows, sandstones, and conglomerates of Pre-Cambrian age, comprising a belt of copper-bearing rock,

chiefly the amygdaloid lava sheets, in which the vesicles, or gas-bubble holes, are filled with calcite, epidote, and zeolites, in which the copper occurs, but it also replaces the rock to some extent. There is some native silver in the amygdaloids.

About one-third of the present production of copper in Michigan is derived from a coarse conglomerate, in which the copper forms fine particles in the cementing material between the pebbles. The conglomerate carries almost no silver.

In addition to the conglomerate and the amygdaloid lavas, there were many copper-bearing veins, which, at first, yielded large amounts of copper, but are not extensively worked at present. They are chiefly veins of metasomatic replacement and contained some extraordinary masses of native copper, one of which weighed 500 tons.

OXIDATION OF ORES — SECONDARY ENRICHMENT

Whenever, by denudation or otherwise, ore bodies, or metalliferous veins, are brought within the shell of weathering, the ores and gangue, like all other minerals, are attacked by the destructive agents and, down to the level of the ground water, at least, very radical changes are produced, for above that level the water is charged with oxygen and carbon dioxide. If there is active downward movement of the ground water along fissures, oxidation may be carried on far below the water table, which limits oxidation if the water is stagnant. Diastrophic movements, denudation, changes of climate may greatly affect the ground-water level, leaving a zone which has been invaded or deserted by the water, as the case may be. In pluvial climates, the water table is not far below the surface of the ground, but in arid climates it may be several hundred feet and oxidation is correspondingly deeper. The products of weathering, of course, differ with the character of the minerals of the vein. Copper sulphides are converted into carbonates, the beautiful green *malachite* and blue *azurite*. Often, the upper part of a vein carrying sulphides is completely leached of its ores, especially if pyrite is present. When exposed to air and water, pyrite is slowly converted into soluble ferrous sulphate ($FeSO_4$), which in time is oxidized into limonite with the liberation of sulphuric acid. Iron is a constituent of most metalliferous veins and when deposited as a mass of limonite, or hæmatite, forms what the miners call the *gossan*. In the deeper, unaltered portion of many

gold-quartz veins, the gold is contained in crystals of pyrite, while above the ground-water level, in the shell of oxidation, the pyrite has been removed and the gold is scattered in minute threads and grains of native metal through a mass of broken quartz, stained rusty red or brown by iron oxide.

Below the level of oxidation is that of the secondarily enriched sulphides, carried down from the leached portion of the vein by the aid of the sulphuric acid. These concentrations often make the richest and most productive part of the vein. The deeper part of the vein carries the primary sulphides and is much less productive of metal values than the secondarily enriched portion; the formation of secondary sulphides is a very complex chemical process, differing according to the metal involved, but into these details it is not possible to enter here. The essential part of the process is that primary sulphides in the shell of weathering are rendered soluble, carried down below the water table, and reconverted into richer sulphides.

E. Deposits in Sedimentary Rocks

Aside from the metalliferous veins which traverse rocks of all kinds, ores in sedimentary rocks may be placed in two classes: (1) *syngenetic*, those which were deposited as a part of the strata and at the same time, and (2) those which were subsequently introduced, or *epigenetic*.

1. Syngenetic Ores: 1. *Iron.* Bog-iron ores are, at present, accumulating in lakes, swamps, and bogs (see p. 353), partly by chemical precipitation, partly through the activity of bacteria. When deposited in the presence of free oxygen, the ore is hæmatite, or limonite; where oxygen is excluded, the carbonate, siderite, is thrown down. Oölitic ores, mostly of hæmatite, are found in many sedimentary rocks under conditions which seem to demonstrate their syngenetic origin. This was shown for the hæmatites of the Silurian stage called Clinton, which extend from New York to Alabama, attaining their greatest development in the Birmingham, Alabama, district, where they are extensively mined, yielding about eight per cent of the total iron ore tonnage of the United States.

Iron deposits, excepting glauconite (p. 395), do not appear to be forming in the modern seas, but in Pre-Cambrian and Palæozoic times oölitic hæmatite and mixed ores were repeatedly deposited

in shallow seas. In Newfoundland, the oölitic Wabana ores are very extensively mined; these are principally hæmatites but contain more or less siderite and chamosite, a chloritic iron mineral. They occur in Ordovician strata and their syngenetic nature has been proved. Thin beds of oölitic pyrite, also laid down in the sea, are found in the Wabana district. Chamosite-hæmatite deposits are very widely distributed. In the Pre-Cambrian of Brazil very valuable and extensive deposits of hæmatite, not oölitic in structure, occur in sandstone and are plainly syngenetic. Much the most productive iron ores of Europe are the oölitic limonites of Lorraine, in eastern France, which occur in horizontal strata of Jurassic date; the ores are local bodies, of lenticular shape.

Siderite ores, which were formerly of considerable economic importance, occur in marine Palæozoic strata in the Appalachian region from Pennsylvania to Kentucky and in Ohio. The "clay iron stone" ores, as they are called, are often in layers of concretionary nodules, which, like other concretions (p. 414), were formed after the deposition of the beds.

The principal iron ore supply of England is derived from marine Jurassic beds in Yorkshire. The ores are called "chamositic sandstone" and "chamositic, siderite sandstone"; the chamositic ore is partly in oölites, but the siderite is rarely so.

2. *Manganese* is found in sedimentary rocks, but much less extensively than iron; all igneous rocks contain it in minute quantities and it is dissolved and carried away as a carbonate and precipitated chiefly as the black oxide, MnO, or, more rarely, as the carbonate. The largest known deposit is in southern Russia (the Georgian Republic) and the ores are found in marine sandstones and clays of the early Tertiary period. There may have been some enrichment.

3. *Copper*. Syngenetic copper ores in stratified rocks are rare; one of the very few that are of industrial importance is the black, cupriferous shale (Kupferschiefer) of Permian age, at Mansfeld in Germany, which has long been mined. The copper is distributed in minute particles of the sulphides through the shale, which is full of the fossils of land plants and was evidently a marine mud, largely organic, laid down in shallow water near the land. The origin of the copper has been much discussed; most German geologists have concluded that the metal was brought in in solution, probably as a sulphate, from the adjoining desert shores. The quantity of

vegetable matter in the mud would reduce the sulphate to sulphide. It has been suggested that the sulphur bacteria were the agents of deposition.

Ores of Weathering

It was shown above that metalliferous veins in the shell of weathering were leached in the upper portion and greatly enriched below by the deposition of the sulphides carried down from above. A somewhat different set of conditions results in the formation of residual ores, left behind and more or less concentrated as other constituents of the rocks are removed. In the southern Appalachian region, from Virginia to Alabama, are many "pockets" in limestone and other rocks which are filled with clay having numerous lumps and nodules of limonite derived from weathered rock. Other ores replace sandstone and limestone along the flanks of the major anticlinal folds. These ores have long been mined, but with diminishing production.

The great iron ore deposits of Bilbao, in northern Spain, which are very extensively worked, are largely residual, as are also three newly discovered districts in eastern Cuba, in which oxidized ores form superficial sheets, the residue from the weathering of serpentine.

Most of the supply of *manganese* is derived from residual deposits. In the United States there are many scattered areas which can produce manganese, as in the Appalachian region, in Arkansas, Montana, and California, but only a small proportion of the needed supply is of domestic origin, more than six-sevenths being imported from Russia, Brazil, West Africa, and India. The Russian deposits, as mentioned above, were laid down in marine strata, but the Indian, African, Brazilian, Central American, and Cuban deposits are residual.

Lake Superior Iron Ores. This area, which is chiefly in Minnesota, but extends also into Wisconsin, Michigan, and Canada, supplies 80 to 90 per cent of the American output and more than one-third of that of the entire world and is the most productive of all known iron ore regions. The ores are chiefly hæmatites concentrated by the action of surface waters from iron-bearing sedimentary rocks of Pre-Cambrian age. In their original form the iron compounds were carbonates and silicates, chemically deposited and interstratified with slate and quartzites. Percolating waters,

of meteoric origin and containing CO_2 in solution, have decomposed the iron compounds, producing the ferruginous cherts and jasper of the region. Later, descending waters leached much of the silica, leaving high grade, usually porous masses of hæmatite. The process is somewhat analogous to the secondary enrichment of metalliferous veins, described above. By this concentration the proportion of iron is more than doubled, increased from an average of 25 to 50 per cent. The work was achieved in very ancient times; at present, very little deposition of iron is taking place.

2. **Epigenetic Ores** are those which have been introduced after the formation of the rock, or, if not actually brought in from outside, concentrated and deposited since the formation of the beds. The ores in sedimentary rocks are copper, lead, and zinc; the first is usually of no great industrial value. While some of these deposits are of doubtful origin, they are generally held to be concentrated by surface waters, which have leached the metals from inclosing or more or less distant rocks.

Copper is very widely disseminated in sandstones and shales which overlie or are a part of the "Red Beds," in the southwestern United States. The Red Beds are Pennsylvanian, Permian, and Triassic in geological date, are of continental origin and were laid down in an arid climate. The copper was introduced in solution from older rocks, and frequently fossil wood in the sandstone is replaced by copper sulphides. In New Mexico, where the cupriferous beds are mined, was found a fossil tree-trunk, 60 feet long, which was almost completely converted into copper sulphides. Copper-bearing sandstones have long been mined at Coro-Coro in Bolivia. In the Triassic sandstones of Europe, which were also deposited under arid conditions, and in the Permian sandstone of western Siberia, there is a great deal of disseminated copper, some of it successfully mined.

Lead and Zinc in Sedimentary Rocks. These are found all over the world and are of remarkably uniform character, being everywhere found in calcareous rocks, limestones, dolomites, cherts derived from limestone, or calcareous shales. The ores are sulphides, near the surface oxidized as sulphates, carbonates, and silicates. A little iron sulphide, usually as marcasite, and small quantities of copper or silver may be present, but gold, antimony, and arsenic are entirely wanting. The ores are either in breccias or crevices, or they form flat "runs" of metasomatic replacement,

following some bedding plane. In the Palæozoic limestones of the Mississippi Valley, especially in the adjoining parts of Missouri, Kansas, and Oklahoma, are the most productive deposits. Similar deposits are found in Triassic limestones of Polish Silesia and the Austrian Alps; Silesia is one of the most important zinc areas in the world. There are great deposits in the Palæozoic limestones of Santander in Spain, on the island of Sardinia, and in Rhodesia. The latter deposit is of zinc, lead, and vanadium, and the ores are replacements along the fissures and bedding planes of a dolomite, date unknown.

The occurrence of the sulphides of zinc and lead in limestone is thus a world-wide phenomenon and a very puzzling one, for which there is no generally accepted explanation. Most geologists believe that the minutely disseminated particles of the ores in limestone and shales have been concentrated through solution and redeposition by meteoric waters. According to some students of the problem the action has been by means of descending waters; others look to ascending waters, derived originally from the surface, while others, again, would appeal to thermal waters rising from deep-seated intrusions. In the present state of knowledge, it is not possible to decide between these alternatives.

F. Placer Deposits

Placer deposits are those of the heavy metals, chiefly in river gravels, but sometimes in beach sands, as at Nome, Alaska. The weathering of auriferous veins gives rise to particles and lumps of gold which, after transportation in swift streams, sink to the bottom. The gold remains on the "bed rock" or in the lower part of the gravels, diminishing upward, until, near the top of a thick mass of gravel, there is practically no gold at all. The gold is concentrated exactly as are the heavier minerals on a stream bed, according to its specific gravity and the size of the particles, which diminishes down stream, because the velocity of the current decreases in that direction. The same rule applies to mineral particles of all kinds, but gold is so very much heavier than the ordinary rock-forming minerals, that only very fine particles are carried far.

About 10 per cent of the annual output of gold throughout the world is derived from placer mines, and these are mostly in countries new to European settlers. In the countries of Europe, such as Spain, Italy, Hungary, and Bohemia, which once had profitable

placer mines, the deposits have long been worked out. But all along the Pacific coast of North America, especially in California, British Columbia, and Alaska, placer gold is still extensively mined. In Victoria, Australia, is another and very celebrated region of placer deposits, especially remarkable for the large nuggets of gold which have been found there, one of which exceeded 200 pounds in weight. Large nuggets have also been found in California, but they are somewhat smaller than those from Australia.

1. *Platinum* has hitherto been almost entirely derived from placer workings, especially those in the Ural Mountains of Russia, but the magmatic ores of South Africa (p. 514) may become an important source of supply. *Tin* is also largely produced in placer deposits, the *stream tin* of the Malay Peninsula, which supplies some 60 per cent of the world's consumption, being cassiterite in river gravels. An additional 10 per cent is taken from placers in islands near Sumatra, China, western Africa, and Australia.

2. *Gold-bearing Conglomerates.* The placer deposits are nearly all of late geological date, Tertiary and Quaternary, because such thin and loose deposits on the land could not be expected to escape denudation. In a few instances, however, gold-bearing gravels have been consolidated into rock, and some of these are mined. A little is obtained from Cretaceous conglomerates in Oregon and California. In the Black Hills, Cambrian conglomerates, truly called "fossil placers," have been mined.

3. *Gold Fields of the Transvaal, South Africa.* These wonderful mines supply about one-half of the world's annual gold production, some $200,000,000. The gold is found in a syncline which is about 120 miles along the strike, the outcrop of which forms the Witwatersrand, a prominent ridge, and the gold occurs in several beds of conglomerate. The series of strata consists of somewhat metamorphosed quartzites and slates interbedded with the gold-bearing conglomerates. The geological age of these beds is not determinable, because of the entire absence of fossils from all of them; the maps merely assign them to some "pre-Devonian" date. The conglomerates are not very coarse, having pebbles of about two inches in diameter, or less, with a sandy matrix inclosing them, which has been made very hard by the deposition of silica between the grains. The matrix has a large quantity of pyrite, which makes up about 3 per cent of the rock and the gold, in almost microscopic shreds and particles, is associated with the

pyrite in the sandy matrix, not in the pebbles, which are mostly quartz.

Despite long and intensive research and much debate, there are still great differences of opinion among geologists and mining engineers as to the origin of the gold; there are difficulties in the way of any explanation. The opinion which is, at present, most widely held is that the conglomerates are ancient placer deposits, in which the gold has been recrystallized. Many excellent workers, however, regard the gold and pyrite as epigenetic and as having been introduced after the deposition of the gravels.

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CHAPTER XXIV

LAND SCULPTURE

The conception of the geographical cycle, consisting of youth, maturity, and old age, was introduced in connection with the development of rivers (p. 279), but is as applicable to the topography of a region as to its rivers. Indeed, the two usually go together, for rivers are a very potent agent in the development of land surfaces. If not interrupted by a diastrophic elevation, the destructive agents, the work of which was described in Chapters XI to

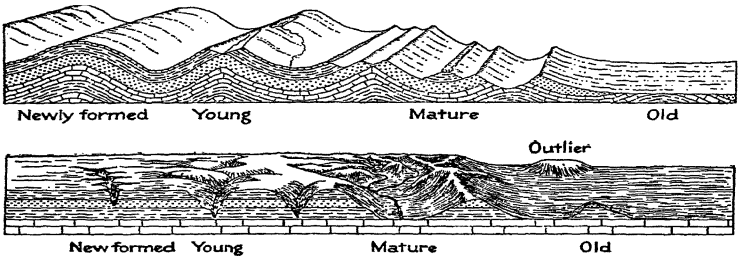

FIG. 256. — Diagrams of topographic changes with age. Upper model in folded strata, lower in horizontal. (G. H. Ashley)

XVII, would cut the land surface down to a featureless plain, and even this would eventually be swallowed up by the sea. The surface of the low-lying land, nearly, but not quite a plain, is called a peneplain and represents the last stage of a geographical cycle. Another term which means almost the same thing is base-level, already used in connection with rivers. A region is base-leveled when it has been denuded to such an extent that the subaërial agents of destruction have almost ceased to operate. This is rather more advanced than the peneplain, but the difference is not great.

If, now, the peneplain should be diastrophically raised into a plateau, all the destructive agents would be rejuvenated, for the driving force of most of them is gravity. The renewed attack would run the same course as the previous one and end in the same way. Thus the course of topographic development from peneplain to peneplain constitutes the geographical cycle. Cycles are seldom, if ever, complete; before one has reached its end, it is interrupted by a crustal movement, which, if upward, begins a new cycle before the preceding one is finished, and if downward, may submerge the whole region beneath the sea and thus put an end to all topographical development of that area.

It is only fair to say that this conception of the geographical cycle is rejected by many geographers and geologists, especially in Germany, and it is not yet possible to decide between the rival hypotheses. Nor can the controversy be taken up here, as that would be unsuitable for an elementary textbook. To allow nationalistic feeling to influence one's judgment in scientific matters would be the height of folly, yet the ideas worked out by a succession of eminent American geologists and geographers, and especially by Professor W. M. Davis, seem to be the best explanation of the American scene.

When an unfinished cycle is interrupted and a new one initiated, certain remnants of the old topography may long persist and give material aid in reconstructing the steps of change.

While the denuding agents will, if allowed the needed time, remove all topographical features and reduce the land to a peneplain, yet, for a long period, denudation will increase irregularity of surface, but it operates with much greater rapidity and effectiveness along certain lines, usually those of the streams, than along others. River valleys are rapidly cut down to base level, but the divides between them are worn away very much more slowly. A plateau which is sure to be removed in its entirety will first be "dissected," cut up into blocks, which, in turn, are slowly worn away. So long as there is a strong contrast between mountain and plain, hill and valley, a region is said to possess *relief*, and maturity of development is reached when the maximum of diversification is reached. In short, erosion does not operate like a plane, smoothing a board, but like a gouge, which cuts away line after line, until the junction of the lines produces an approximately plane surface.

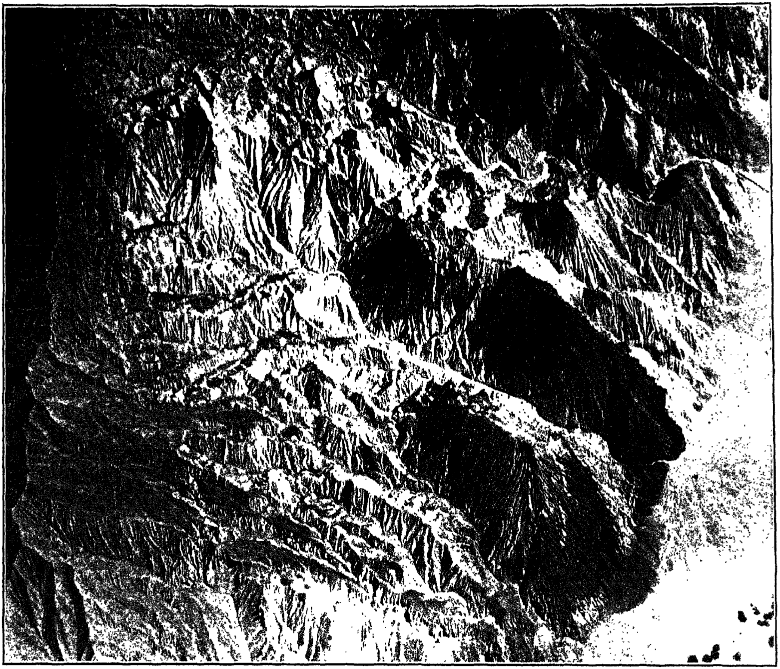

Fig. 257.—Mature topography, Death Valley, Calif.; floor of valley in lower right corner. (Courtesy of the Chief of Air Corps, U. S. Army)

Primarily, relief is due to the struggle between diastrophism, which, on the whole, increases the height of land, and denudation, which sweeps it away, but while relief lasts, many more factors enter into the problem. The topography of any region is the resultant of the very complex interaction of many factors, active and passive, antecedent and subsequent. By no means all features

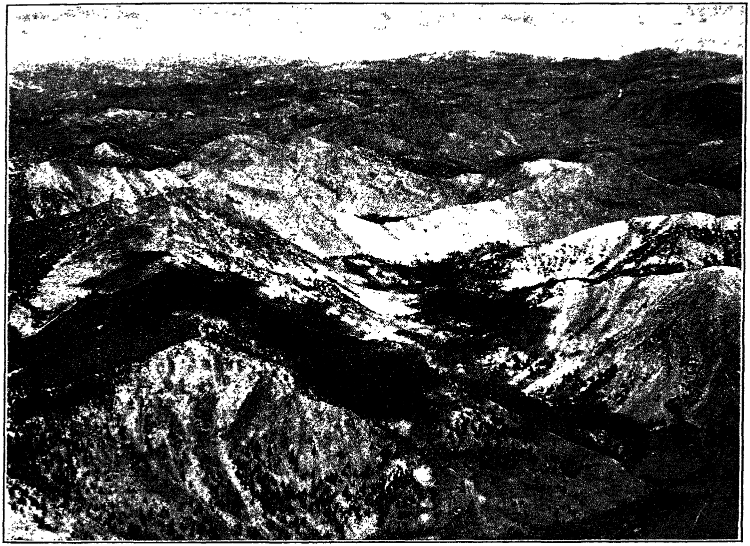

FIG. 258. — Mature mountain topography, Sawtooth Range, Idaho. (Courtesy of the Chief of Air Corps, U. S. Army)

of relief are formed by destructive action, for many such features are the outcome of constructive activity, but these constructions are attacked in their turn and removed. Volcanic mountains and plateaus, plains made by deposits on the sea bottom subsequently raised into land, alluvial plains of rivers; the hills, ridges, and drift sheets made by glaciers and the waters derived from their melting, are examples of constructional topography.

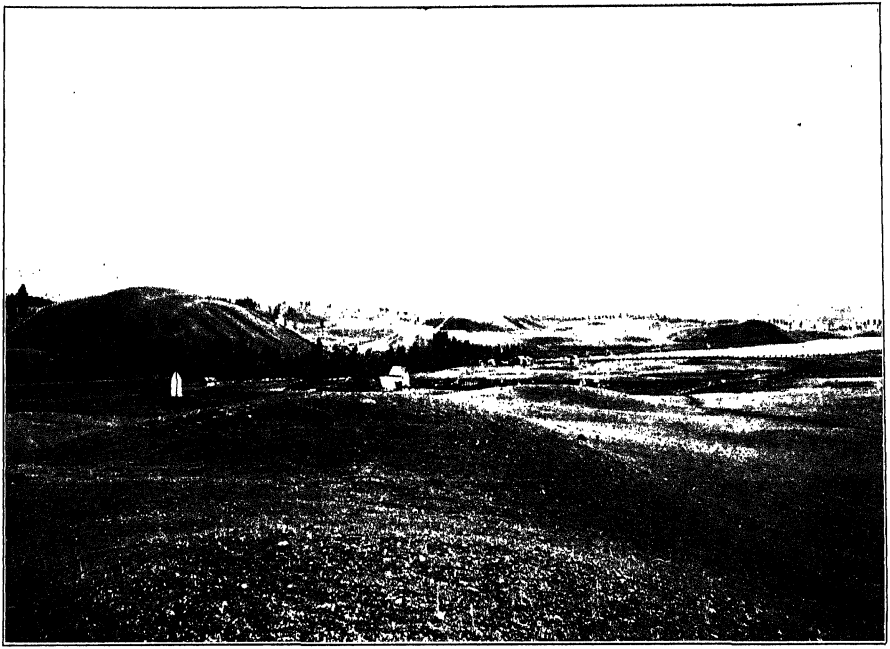

FIG. 259. — Glacial topography, Tobacco Plains, Wash. (Photograph by Willis, U. S. G. S.)

Another type of topography is the *tectonic*, in which the main features are due to orogenic processes, more or less modified, it may be, even reversed by subsequent denudation. In tectonic relief the ridges are anticlines and the valleys synclines, and fault scarps are lines of cliff, low or high.

Each of the great eroding agents has its characteristic forms of relief and as one or other of these prevails in a region, the topography changes accordingly. Which is as much as to say that, away from the seacoast, differences of climate are reflected in differences of topography, for climatic differences are merely another expression for the preponderance of this or that agent of erosion. The polar lands have glacial topography. The relief of pluvial and temperate regions is entirely different from that of arid and desert regions; in one case rain, frost, and running water are the sculpturing agents, and in the other, the heat of the desert sun and the cutting blast of wind-driven sand. Tropical topography, whether or not veiled by a dense cover of vegetation, is different from that of any other climate, because of the absence of frost and snow, save from the tops of high mountains, and the extraordinarily active work of the rain in chemical decomposition of the rocks. Immense rivers are characteristic of tropical and subtropical climates, because of the great rainfall and its mechanical effects. Every climate thus has the topography which expresses its characteristics.

All of the preceding factors which control the development of relief are active, dynamic, but there is another, no less important series, in which the factors are entirely passive, and that is the character and arrangement of the rocks, whether hard or alternatingly yielding and resistant to disintegration, whether sedimentary, igneous, or metamorphic. As most of the land is made up of sedimentary or stratified rocks, the attitude of the strata, whether horizontal, tilted, folded, or faulted, has a most important bearing upon the resulting topography and, in regions of igneous rock, the form of the volcanic or plutonic bodies, cones, flows, dykes, sills, etc., etc., is still another determinant. The crystalline schists, when forming the peaks and ridges of high mountains, weather with a characteristic and unmistakable ruggedness, unlike that of other rocks.

Constructive processes of accumulation, especially when working in conjunction with diastrophic movements, may completely bury an ancient topography out of sight, substituting a new and

different kind of surface for the denuding agents to work upon. When the vast floods of basaltic lava were poured out over the surface in eastern Africa and the northwestern United States, they filled up all the valleys and buried the hills, leaving a flat-topped plateau, which had no relief other than distant mountains. On the Atlantic coast the ancient land surface was buried in another way. The floor underlying the Coastal Plain is a rugged surface of crystalline schists which, by flexing or down-faulting, was submerged beneath the sea during the latter part of the Cretaceous period. How far inland this Upper Cretaceous sea encroached is a matter of debate, but it may have been over the site of the present Appalachian ridges. When the reëlevation took place, there was a smooth plain, sloping gently seaward and made up of loose marine deposits. These have all been swept away to the line of the Coastal Plain and, west of that, the old topography was brought to light and subjected to further modification.

The resurrection of ancient land surfaces of relief may go back much farther in time than this relatively late instance of the Coastal Plain. In the Charnwood Forest (Leicestershire) in England the ancient land surface of Permian times, which was of Archæan rocks, with intrusions of granite, is being resurrected by the denudation of the soft overlying rocks, thus creating "a patch of highland scenery in the very heart of the English plain." (J. A. Howe.) If a rough calculation be made of the permutations and combinations of the many factors which enter into the determination of topographical features, it will readily be seen that the endless variety of scenery and landscape is accounted for. In a broad, general way, each climate has its characteristic features of land relief; in details, the boundless variety is astonishing. The only topographical forms that are everywhere alike are featureless plains.

There is one general principle which applies to the forms of relief in all regions where the rocks carved by erosion are heterogeneous, some beds or masses being harder than others. In this connection, the word *hard* means resistant to denudation, and in the great majority of cases the ordinary meaning of the word also applies. Sometimes a soft rock resists weathering better than a hard one because of its chemical composition. The general principle above referred to is that the soft rocks are more readily worn away, leaving the harder ones to stand out in relief. Relief is thus due to

two inequalities, in the operation of the denuding agents and in the hardness of the rocks. In a pavement of stone slabs that has long been worn by the tread of many feet, the originally smooth surface becomes unequal, sometimes because of the lines of maximum traffic, which are more worn, and sometimes because of the harder spots, which wear little or not at all. The analogy with a land surface is quite complete.

A. Land Forms in Stratified Rocks

1. *Horizontal Beds.* A newly raised plateau of horizontal rocks is speedily trenched by the streams in deep, vertical-sided cañons. Weathering gradually widens out the cañons into broad valleys, the profiles of which are determined by the alternation of harder and softer strata. If the beds are relatively resistant, and especially if hard rocks form the surface of the upland, the extension of the ramifying valley system will dissect the plateau into a series of flat-topped table mountains, which in the Southwest are called by the Spanish term *mesa*. The height of the mesas is determined by the depth of the valleys, which, in turn, is regulated by the height of the plateau above sea level. The mesas are attacked by the weather on all sides and, unless protected by a harder cap, are worn into pyramids and cones, just as are the isolated stacks on the sea coast. Isolated fragments of the plateau in the Colorado Cañon form pyramidal mountains, which are dwarfed by their surroundings.

If the whole mass of beds is soft and easily destructible, they will weather into dome-shaped and round-topped hills, as in the bad lands of the Dakotas and Wyoming, the fantastic scenery of which is famous and is the result of the weathering of soft, horizontal strata in an arid climate, unprotected by vegetation. Harder beds in such climates give rise to vertical-sided tables, such as the sandstone mesas so common in New Mexico. Table Mountain, near Cape Town, and the bold headlands, called the Twelve Apostles, which front the sea, are remnants of a plateau of horizontally bedded sandstones. Such table mountains, as the frequency of the name implies, are common in many parts of the world.

If harder rocks lie beneath the softer ones, a change in topographic forms will result when the harder rocks are exposed. In the soft rocks the valley sides have very gentle slopes, while the

hard beds, which retreat chiefly by undermining, have steep faces because of the falling of joint blocks. When harder and softer beds alternate in the valley wall, the soft beds form gentle slopes, connecting the steep, or vertical, faces of the harder strata.

Sometimes the appearance of horizontality is given by very gently folded strata, as in the Uinta Mountains of northern Utah, which are formed by a single enormous anticline, faulted along the northern slope. The curvature is so gentle that, except near the foot of the mountains, where the strata are turned up to a nearly vertical position, the beds, in any single view, appear to be horizontal. Out of these masses of level strata, several thousand feet thick, the subaërial agents have carved the bewildering variety of peaks, ridges, and amphitheaters, which give to these snow-capped mountains the extremely picturesque and beautiful appearance that can be seen from afar across the level top of the high tableland from which the range rises into the region of perpetual snow. Talus slopes on a gigantic scale attest the effective action of frost and give a vivid conception of the amount of material which has been carried away in the sculpturing of these mountains.

2. *Tilted or Inclined Beds.* The strata in tilted fault-blocks are inclined, and parts of very wide folds may appear to be simply tilted, because the curvature is so flat. The Newark sandstones (of upper Triassic age) which fill the Connecticut Valley have an easterly dip, while those west of the Hudson River dip gently westward, and between the two is a broad area, fifty miles or more in width, where Pre-Cambrian crystalline rocks are laid bare. Some geologists believe that the two areas of Triassic rocks have been separated by denudation and that the portion swept away was a folded belt, of which the remaining strata were the flanks and the opposite limbs of anticlines (not of the same anticline). As a matter of fact, it is indifferent whether these and many other masses of inclined beds were once parts of great folds or not, as the resulting topography is the same in either case.

If the inclined strata are made up of harder and softer beds in alternation, the latter will be removed more rapidly than the former, which are left standing as lines of cliff, the height and steepness of which are determined by the thickness and angle of inclination of the more resistant strata. If the beds are steeply inclined, a succession of harder and softer ones, in alternation, will give rise to a series of ridges and valleys, the slopes of which depend upon

the angle of dip. If the beds are vertical, the two slopes of each ridge will be nearly or quite equal, the hard beds forming the backbone of a ridge and the softer ones the sloping sides. Hard vertical beds may be left standing by the removal of the softer ones on each side of them and then they look deceptively like dykes of igneous rock. As the angle of inclination diminishes, the more unequal do the two slopes of each ridge become, the longer and gentler one being in the direction of the dip. Many examples of this type are to be found in the Appalachian Mountains, and an excellent

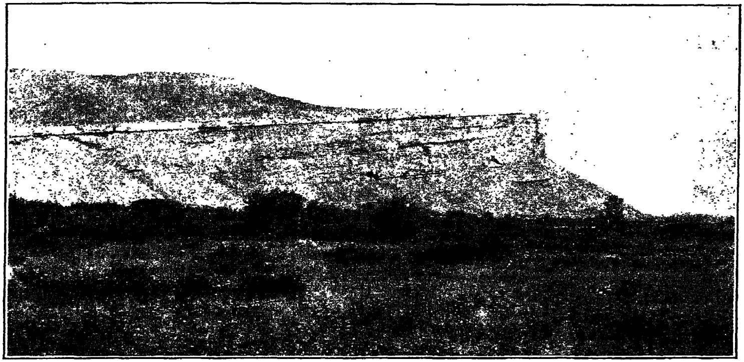

FIG. 262. — Escarpment and dip slope, near Hyattsville, Wyo. (Photograph by Darton, U. S. G. S.)

illustration of it is given by the Kitatinny ridge, which is cut through at the Delaware Water Gap (Fig. 113, p. 266). The crest of the ridge is formed by very hard conglomerates and sandstones, with a steep escarpment, or cliff, on the southern side, while the broad valley above and below the Gap has been cut out along the strike of destructible rocks.

The abruptly truncated, cliff-like outcrop of the hard stratum is, as just noted, called an *escarpment* and follows, with some sinuosities, the line of strike. Whether the escarpment shall follow a generally straight, or a curved course, is determined by constancy, or change, in the direction of dip. The upper surface of the hard bed may be exposed by the stripping of the overlying softer beds,

and then the surface of the ground is formed by the resistant stratum and is called a *dip slope*. A series of gently inclined strata, made up of alternating harder and softer beds, will thus give rise to parallel ridges and valleys, or escarpments and dip slopes, according to the completeness with which the softer beds are removed and the harder ones exposed. A wonderful example of such topography is displayed in the high plateaus of Arizona and Utah, where the dip slopes are from 20 to 60 miles broad and the escarpments 1,500 to 2,000 feet high. The amount of denudation involved in the production of these vast amphitheaters staggers belief, but there is no doubt that it actually took place.

By the eroding agencies the escarpments are slowly but steadily cut back in the direction of the dip. Rain and frost act directly on the hard beds, but cut them back more effectively by undermining, thus causing the unsupported joint blocks to fall. The fallen tálus, in its turn, is gradually disintegrated and washed down into the water courses. The escarpments may follow a relatively straight or a very sinuous course; the sinuosities, when present, are due to the undermining action of springs, which, by the recession of their heads, excavate the line of cliffs into bays and amphitheaters. Every step in the recession of an escarpment lowers the ridge and brings it nearer to base level, because it recedes down the dip. A steeply inclined bed needs to be cut back but a short distance before it reaches base-level.

A plain of marine denudation, or a peneplain worn down by the subaërial agencies in disturbed strata, usually cuts across the bedding planes and is a sloping surface formed by the outcropping *edges* of the strata. The first streams established would follow the slope (consequent streams) and the first valleys would be cut across the strike of the beds, trenching both hard and soft. For a time the hard beds would be in relief and would cause waterfalls, but these are soon removed. Such streams and valleys are said to be *transverse*. As the older consequent streams cut down their trenches, tributary valleys are excavated along the strike of the softer rocks, and these are *longitudinal* or *strike valleys*. In a longitudinal valley, following the strike of weak beds, the stream which occupies it tends to flow along the foot of the escarpment formed by the strong beds and to shift its course laterally in the direction of the dip, cutting away the soft beds and undermining the hard. Such valleys tend to have one steep, or vertical, and one gently

sloping side. The strata dip across the stream and, hence, on one side are inclined toward the valley and, on the other side, away from it. The former is the weaker structure, because the loosened joint blocks glide into the stream, and the ground water, following the bedding planes, forms springs on that side of the valley.

The steep ridges, or *hog-backs*, as they are locally called, so frequent in the foothills of the Rocky Mountains, are the simply inclined descending limbs of monoclines, from which the horizontal limbs have been eroded away. Between the hog backs and the mountains are valleys with longitudinal streams cutting along the strike.

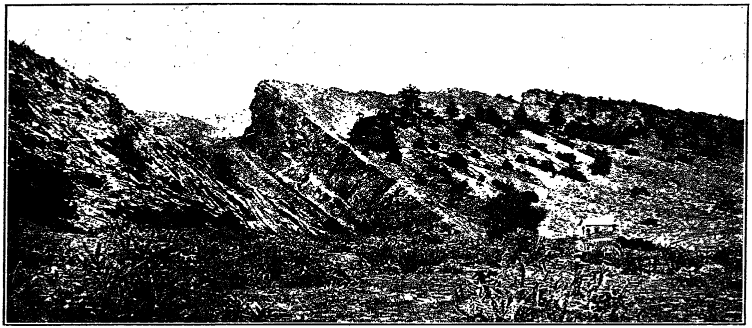

FIG. 263. — Monoclinal hogback with gap through ridge, near Cañon City, Col. (Photograph by Walcott, U. S. G. S.)

3. *Folded Beds*. A region of folded strata is, in the first instance, thrown into a series of ridges and troughs, the ridges formed by the anticlines or saddles. In other words, the topography is *tectonic*, or *structural*, and is due to diastrophic movements. In moderate, or undulating folds, the tendency of denudation is to reverse the tectonic relief and convert the anticlines into valleys and the synclines into ridges, a very common arrangement in the Appalachian Mountains. See also Mont Perdrix in the Canadian Rockies (Fig. 247). This apparently paradoxical result is seen, on examination, to be natural, indeed inevitable. The crests of newly formed anticlines have been subjected to tensile stresses which open the joints of the strata and render them readily acces-

sible to the destructive agents, while the syncline is tightly compressed, the joints of its strata closed by crowding.

There is another factor tending to produce the same result. In a folded series of alternating harder and softer strata, the anticlines are exposed and unprotected, the synclines are soon covered with the débris which washes down from the ridges, and in the exposed anticlines the hard beds are first reached and cut through. When an underlying mass of soft strata is reached, it is rapidly trenched into valleys which may soon be excavated below the level of the synclinal troughs.

The Jura Mountains of northern Switzerland and southern Germany, although they have undergone considerable denudation, still have their principal features of relief determined by the folds which make the valleys and ridges. The range, which measures about 192 miles from east to west, consists of ten or twelve parallel lines of anticlinal ridges, more in some transverse lines than in others, for none of the ridges is continuous for the whole length of the range; they die down and are replaced by others, usually with an offset, not in the same line. In length they measure mostly from 2½ to 55 miles, but one ridge is almost one-half of the length of the range as a whole, 97 miles. This arrangement of many shorter ridges is usual in mountains and comes out very clearly in a relief map of the Appalachians.

Denudation has considerably reduced the height of the anticlines, removing from their summits strata which are still preserved in the valleys and on the flanks of the ridges. Many transverse valleys cut through the ridges connect one longitudinal, synclinal valley with another; Supan's sketch map of the headwaters of the Biss shows that that stream and its tributaries have cut twenty-one valleys through the ridges.

Mountain ranges, which are dealt with in another chapter in greater detail and more at length, are of very different geological dates of origin and, consequently, of very different degrees of denudation. The loftiest ranges, such as the Alps, the Himalayas, the St. Elias range in Alaska, are of very late elevation, relatively speaking. Whatever their date, all of the existing high ranges have suffered great denudation, the more ancient ones in greater degree than the younger chains. Peaks, crests, amphitheaters are all features due to erosion, though the principal ridges be of tectonic origin. Many ranges, like the Rockies and the Sierra

Nevada, have a core of granite, which makes the serrate sky line, for the bedded rocks have been stripped away from the summits. Very ancient mountain ranges, such as the Appalachian, have an entirely different type of topography due but remotely to folding and far more to their history and erosion.

B. Forms in Volcanic Rocks

Volcanic topography is primarily constructive, being built up of the material brought from below the earth's surface and piled upon a land area or sea bottom. Nearly all volcanoes build up cones around their vents, the height and diameter of which are determined by the amount and character of the material and the nature of the eruptions. Some volcanic cones are very lofty mountains, others are not more than 40 or 50 feet high. The shape of the cone is conditioned by the kind of volcanic products of which it is built. The "cinder cones" of fragmental material are very steep and of very graceful form, like the famous sacred mountain of Japan, Fuji San, or the magnificent snowy cones of the Cascade Mountains in Washington and Oregon.

Cones built entirely of lava are much less frequent than the cinder cones and their shape is dependent upon the fluidity or viscosity of the lava. Mauna Loa, in the island of Hawaii, is 14,000 feet high and so extremely gentle are the slopes of the sides that the mountain is 80 miles in diameter at sea level. Measured from the sea bottom, the gigantic cone is 30,000 feet high and 200 miles in diameter at the base. Another form is the crater ring, or *caldera,* which is usually produced by a tremendous explosion blowing off the top of the mountain. On the Alaskan peninsula in an immense crater ring, Aniakchak, more than 13 miles in diameter, and the islands of the Malay Archipelago have many calderas. Crater rings, like Kilauea in Hawaii and Crater Lake in Oregon, were made by engulfing the upper cone, a much less common method.

Like all other mountains, volcanic cones are attacked by the denuding forces, but, so long as the vent is active, erosion is more than balanced by upbuilding, provided that no terrific explosion tears off the top or blows out the side of the cone. A cinder cone built in the sea is swept away after a few weeks' exposure to the waves. On land destruction is slower, but quite as sure, and in all parts of the world and in rocks of nearly all geological dates

may be seen volcanic cones in all stages of degradation and removal. The remarkable volcanic fields of Arizona and New Mexico, where all the vents are extinct, display cones in all stages of degradation. Sunset Crater, near Flagstaff, Arizona, had its last eruption, as is indicated by archæological evidence, about 500 A.D. ± 200 years. The cone and its lava flows are in perfect preservation and look as though activity had just ceased. The beautiful, snow-capped San Francisco Mountains, in the same field, are a craggy group of peaks which rise abruptly from the plateau, but do not otherwise immediately suggest their volcanic origin, because of the way in which they have been eroded. Where nearly all of the cone has been removed and the lava plug, which filled the chimney at the last eruption, is exposed to view, it is called a *volcanic neck*. In Fig. 35 is seen such a neck in New Mexico, and in Fig. 37 (p. 100) the remarkable conical hill, known as Sugarloaf, near Campbellton, New Brunswick, which is a volcanic neck of Devonian times.

In the Canadian province of Quebec and in the northern parts of Vermont and New Hampshire are several cylindrical plutonic bodies, believed to be the roots of volcanoes which were active in the Carboniferous period. In Quebec these are called the Monteregian Hills, of which Mount Royal, at Montreal, is one, and are arranged in an east-west row. Most of these have been eroded below the base of the ancient volcanoes and form hills of the cylindrical pipes filled with hypabyssal rock. Mount Johnson may be called a volcanic neck. In South Africa and Arkansas the diamond-bearing pipes have been so completely denuded that all trace of them on the surface has been removed.

Another type of volcanic topography is exemplified in the immense lava plateau of the Pacific northwest, which is over 200,000 square miles in extent. This plateau is of relatively late geological date and has not yet been extensively cut up; no doubt the semi-arid climate is the reason for that. The streams have cut cañons down through the lava, and some of the valleys have been widened considerably, but in looking across the plateau, the trenches are hidden and the region seems to have been hardly modified at all. An even larger mass of lava, piled up in successive flows, is in the Deccan in India. Another great lava field is in East Africa and is thus described by Gregory: He saw from the top of the Ivesti Mountains a great, undulating plain, extending to

the western horizon, "the rock of which this consisted ended abruptly against the flank of the old gneiss ridge, but it ran up the valleys and into the hollows of the mountains, just as the water of a lake follows the irregularities of its shore. So much did this view remind me of that across the Great Snake River lava fields of Idaho, when seen from the range of the Tetons, that I felt sure at once that this was a plain of lava and not of alluvium. I hastened down to it and the inference was confirmed." (Gregory.) The dissection of a lava plateau proceeds as though the successive lava flows were horizontal strata of sedimentary rock, except that lava is harder than most stratified rocks. In the west of Scotland and the north of Ireland is a lava plateau of much more ancient date than those hitherto mentioned, which has been so cut to pieces that its original character is greatly obscured. It is believed that this immense lava plateau extended to Iceland and has been broken up partly by erosion, partly by diastrophic subsidence.

C. Forms in Plutonic Rocks

It is exceptional to find topographical features that can be referred to the direct tectonic effects of a plutonic intrusion for the obvious reason that the existence of a plutonic body at a given point can seldom be determined until the body has been exposed by denudation. Laccolithic hills and mountains are of this exceptional character; for the dome-shaped covering of stratified rock is often more or less preserved. In the Henry Mountains of southern Utah, where laccoliths were first discovered and named by the late Mr. Gilbert, these remarkable intrusives formed a series of dome-like uplifts, irregularly scattered, not forming a range, and they have been deeply dissected by erosion, so that the form of the plutonic masses and their relations to underlying and overlying strata can be determined.

Another group of laccoliths is northeast of the Black Hills of South Dakota and displays successive stages of denudation, from Little Sundance Hill, with nearly intact cover of strata, to Mato Tepee, the remnant core of the intrusive body. Shonkin Hill near the Highwood Mountains of Montana is a laccolith dome so cut into and exposed by a ramifying gulch that its structure is completely laid bare, and yet much the greater part is intact, displaying the topographic form due to the doming of strata by an igneous

intrusion. Shonkin Hill is an unusual form of laccolith because of its long, low profile and steep border. (Figs. 16–23.)

The effects of other types of plutonic bodies upon the relief of land surfaces is due to the shapes of the intrusive masses themselves, as they are uncovered by denudation. Ordinarily, the igneous rock of the plutonic mass is more resistant than the inclosing country rock and therefore stands out more and more prominently as the country rock, usually stratified, is eroded away. The shape of the resulting topographic features is that originally taken by the plutonic body, as it forced its way upward into the higher regions of the earth's crust, following the paths of least resistance. It sometimes happens, on the other hand, that the plutonic mass is weaker and less resistant than the inclosing rocks, and then, when exposed, it weathers faster than the country rocks and gives rise to a depression. Sometimes this is a matter of climate, the same kind of igneous rock decomposing much more rapidly in a warm than in a cold climate.

The commonest form of intrusive body is the dyke (p. 71) which cuts across the strata at high angles, sometimes filling vertical fissures, more frequently steeply inclined. Dykes vary greatly in dimensions, from a length of a few feet to hundreds of miles and from a thickness of a few inches to many yards. Always, the dyke is very long in comparison with its thickness. When exposed by erosion, a dyke forms a wall, sometimes many intersecting walls appear, which seldom exceed 40 to 50 feet in height, because the igneous rock is likewise subject to attack, and the thinner and the more inclined from the vertical the dyke is, the more is its height limited. In the glaciated parts of the continent, dykes and including rocks were worn away at the same rate by the ice, and though a dyke may be very conspicuous in a cliff because of contrasts in color, it seldom rises above the surface of the ground, while in unglaciated areas, as in Colorado, Wyoming, Montana, the walls of dykes are frequent and conspicuous.

Sills, as previously pointed out (p. 74), are concordant with the bedding of the strata into which they intrude, but not seldom cut through from one level to another. A sill is always connected with one or more, sometimes a large number of dykes, which have filled the fissures through which the magma of the sill rose. In its topographical results a sill behaves like a stratum, usually much more resistant than the sedimentary rocks which bound it above

and below. Like other plutonic masses, sills vary greatly in dimensions, and much the largest and most imposing one in the eastern United States is that of which the exposed edge forms the famous Palisades of the Hudson, so called because of the roughly columnar jointing of the trap rock. For more than thirty miles, in a nearly straight line, the Palisades are the towering cliffs of the west bank of the river. How much farther eastward the sill formerly extended cannot now be determined. On the top of the cliff patches of the sandstone cover may still be seen, and westward, the great mass dips gently beneath the band of Newark sandstones and shales that crosses New Jersey. The great sill extends some forty miles to the southwest, where it again comes to the surface in Rocky Hill, a low ridge of trap (diabase) that extends to the Delaware River. Many borings that have been put down for wells and similar purposes have shown that there is, in fact, uninterrupted continuity between Rocky Hill and the Palisades, though only the two edges are exposed to view.

Another type of plutonic body is the *stock* (p. 68) or *boss*, a more or less conical, or dome-like, or irregular mass, which broadens downward to its junction with the parent body from which it is given off. It differs from the sill and laccolith in cutting across the strata of country rock and not in lifting or doming them. As they are exposed by denudation, stocks give rise to hills, the shape of which is that of the original intrusive body. The more denudation exposes them, the greater their relative height above the surrounding country. Snake Hill and Little Snake Hill, which rise out of the Newark Meadows, are stocks given off from the Palisades Sill. Stone Mountain in Georgia is a stock of granite, from which not only the inclosing country rock has been stripped away, but also the outer circumference of the granite stock itself has been removed. (See Figs. 4–7.)

In the northern part of the broad band of Newark sandstones, which in the Connecticut valley, in New Jersey, and Pennsylvania is so extensively intruded by plutonic bodies and has so many volcanic flows and accumulations, the igneous rocks are more resistant than the sandstones and form the prominent topographical features. Mount Tom and Mount Holyoke in Massachusetts, East and West Rocks at New Haven, the Palisades, the Snake Hills, Orange Mountain, the Watchung Mountains near Paterson, the Sourland Mountains, and Rocky Hill are all prominent igneous

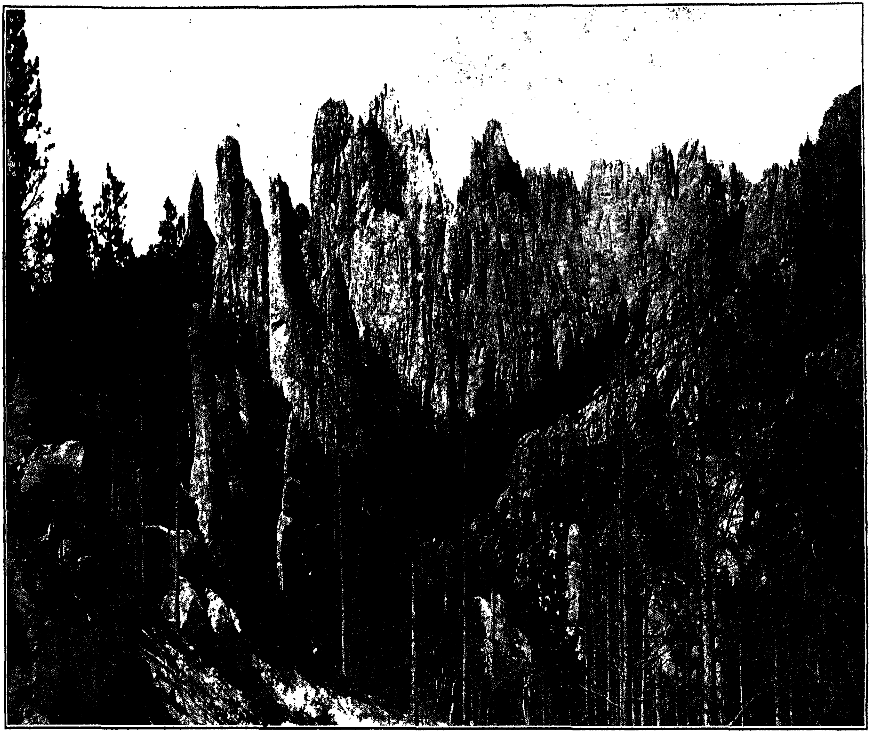

Fig. 264. — Granite "needles," Harney's Peak, Black Hills, S. D.

masses, some volcanic, but mostly plutonic bodies laid bare by denudation. The Newark formation also extends into North Carolina and is accompanied by the same kind of igneous rocks, but there the latter weather more rapidly than the sandstones and form depressions instead of prominences. Dykes are trenches partly filled with the clay derived from the decomposition of the feldspar of the trap, instead of outstanding walls. The same thing has been accomplished by the sea on Cape Ann, Massachusetts, which has cut a trap dyke into a trench, as also on the coast of Inverness-shire, in Scotland.

Except in mountain ranges, the batholiths, largest of all plutonic masses, do not form prominent features in the topography of a region, but all relief, it must not be forgotten, is relatively transitory. Whatever the structure of a rocky coast, the horizontal saw of the surf cuts it into a low plain, sawing through horizontal, inclined, folded strata or igneous masses at different rates, but with equal certainty. Inland, the subaërial agents first produce relief by differential erosion and then proceed to remove it, smoothing the most rugged surface into a peneplain.

D. Topography Due to Faulting

Faults, as was previously shown (Chap. XIX), are fractures and dislocations of the rocks, whatever their nature. On the two sides of the fracture the rock masses have moved differentially; it is not always possible to determine the actual direction of movement, but the effect is as if one side had been raised, the upthrow side, and the other, the downthrow side, had been lowered. Faults are seldom vertical and are usually steeply inclined; in a normal or gravity fault the plane of fracture inclines toward the downthrow side, as though that side had settled down and, no doubt, that has frequently happened. In a reversed fault the slope is toward the upthrow side, as though that side had been pushed up, and, very probably, that has often been the case.

Faults that have been observed to originate or increase in modern times have been associated with earthquakes; the fault in Yakutat Bay, Alaska, which accompanied the earthquake of 1899, had a throw, or vertical displacement, of 47 feet. The San Francisco earthquake of 1906, the Japanese of 1891, and countless others were connected with faults of 5 to 20 feet throw, and the result of the faulting is the formation of a scarp or line of bluffs

that may run for hundreds of miles. Repeated movements along the same fault plane often have resulted in displacements of many thousand feet, but no movements on such a scale have been observed in our day, for they are the cumulative effects of movements through long periods of time.

In climates of abundant rainfall the fault scarp is worn away with relative rapidity, so that both sides are reduced to the same level, or to the same continuous slope, all surface indications of the fault being removed or concealed. In arid climates the scarps may persist, even in loose materials, and, in favorable conditions, they may long remain conspicuous, even under very heavy rainfall, and dominate the topography. Faults do not ordinarily occur singly, but in multiples, which are arranged, sometimes, in definite systems, parallel, branching, intersecting; in other cases they are irregular and conform to no obvious pattern. The topographical forms resulting from these multiple or compound faults are determined by the amount of the displacement and, in the second place, by the relations of the various slopes of the fault planes to one another. A series of step faults (p. 440), so long as the scarps persist, forms an enormous staircase. Each step is a fault-block (p. 446) and may be horizontal or tilted, and the fault planes of the steps all slope in the same direction. If large enough, fault blocks, whether steps or horsts, are called block mountains, especially when tilted and cut into rugged forms by denudation.

The Great Basin of Nevada and Utah is bounded on the west by the gigantic fault scarp of the Sierra Nevada and on the east, 800 miles away, by the lower fault scarp of the Wasatch Mountains. Both of these mountain fronts have been made so irregular and rugged by erosion as to conceal their true character. Several parallel mountain ranges, collectively called the Basin Ranges, which have a north-south course, are likewise much eroded fault blocks, which have been more or less strongly tilted. The Vosges Mountains in France and the Black Forest in Germany are two horsts, which face each other across the broad and deep trough of the Rhine Valley. A similar block rises 3,600 feet above the African plateau, itself nearly 4,000 feet above sea-level. On a smaller scale, horsts occur in almost every complexly faulted area.

If two parallel faults incline toward each other, converging downward, the block between them is depressed and is on the downthrow with reference to each side. This is called a trough or

trench fault, or a rift valley, if on a sufficiently large scale. The middle portion of the Rhine Valley is a trench, the formation of which opened the course of the river to the North Sea. Between the horsts of the Black Forest on the east and the Vosges Mountains on the west lies this deep trench, where the Rhine has cut a channel in the thick mass of its own deposits, laid down on the rocky floor of the *Graben*.

By far the most remarkable instances of fault topography are the Great Rift Valleys of Africa, which are more than 1,000 miles in north to south length. "Once the plateaus of Mau and Kikuyu were continuous across the site of the Great Rift Valley; a double series of north and south [faults] cut through the plateau allowed the block of material between them to subside. This left a great open Rift Valley. . . . Strips of country have fallen, owing to a series of parallel cracks or 'faults' and thus a valley has been formed with precipitous and sometimes step-like sides. . . . Great earth movements have happened so recently that rock scarps, 1,000 to 2,000 feet in height, still stand bare and precipitous as though formed but yesterday and straight lines and sharp angles still dominate the scenery. The recent date of such earth movements has therefore rendered the physical features of the country such a direct expression of its geological structure, that this can be recognized in a hasty traverse." (Gregory.)

Professor Willis, who made a study of the region in 1929, writes: "There are two great zones of fracture in eastern Africa which are more or less continuous rift valleys or chains of rifts. They form two arcs facing one another, the Eastern and the Western rift zones." The eastern zone is a curved line of some 650 miles in length and 20 to 30 in width, and the western one is 850 miles long, the two meeting south of Lake Tanganyika, which is profoundly deep, more than 4,000 feet, with its bottom 1,600 feet below sea level. Not all of the valleys are bounded by fault scarps on both sides; there may be a scarp forming the wall of the valley on one side, while the other side is a sharp flexure; these two kinds of displacements frequently pass into each other. The floor of the Rift Valley is very uneven and contains no less than thirty lakes; and several volcanoes, some of them still active, broke out in the Rifts."

In Syria there is a rift valley known as the Ghor, of which the northern end is not far from Damascus; it forms the whole valley of the Jordan and that of the Dead Sea, and for much of its length

it is below the level of the Mediterranean. The Sea of Galilee is more than 600 feet below sea level and the surface of the Dead Sea is more than 1,300 feet below. South of the latter, the floor of the valley gradually rises to sea level at the north end of the Gulf of Akabah, the northeastern branch of the Red Sea. The gulf and the Red Sea are believed to be a continuation of the Ghor and to be connected with the eastern Rift Valley of Africa by the depression which runs southwestward past the plateau of Abyssinia. If the Red Sea, the Gulf of Akabah, and the Ghor are to be properly regarded as a continuation of the Great Rift Valley, then this whole structure is more than 4,000 miles long and is one of the major topographical features of the entire globe.

Whether the features of relief that are due to faulting persist for a long time (geologically speaking) or are speedily removed by denudation, is determined by the relative hardness of the rocks on the two sides of the fracture. If the rocks exposed on the upthrow side are notably more resistant than those on the downthrow side, the scarps may continue for ages, as they have on the eastern and western mountain walls of the Great Basin, the Wasatch, and Sierra Nevada, both fault-scarps. The Highlands of Scotland are made of very ancient and very hard rocks and are on the upthrow side of a great fault, which crosses the island from sea to sea. The Lowlands are on the downthrow side and are built up of younger and less resistant rocks, and thus the difference of level has continued despite the great antiquity of the movement. The Highlands have been very extensively denuded and carved into such wild and rugged forms as to disguise their essential character. The southern part of Scotland, south of the Lowlands, is a subordinate highland, or upland, which likewise forms the upthrow side of a fault, exposing more resistant rocks than those of the Lowlands, which are thus another rift valley.

A section across the high plateaus of Arizona and Utah shows that, on the eastern side, the high plateau descends to a lower one by means of a flexure, or monoclinal fold, while on the western side the plateau is bounded by fault scarps.

The topography of eastern Asia is dominated by a series of gigantic faults; the coastal plain of China is cut by parallel faults into blocks, with downthrow to the east and a westward tilt. On the west is the Mongolian block, then comes the Manchurian block, and, on the east, the partially submerged Japanese block. The

tilting brings the eastern edge of the block above water, while the western is submerged. The chain of islands which fringe the eastern coast of Asia, from Japan to the Arctic Circle, is carved from the edge of the tilted block. The peninsula of Korea has been compared to a chessboard of fault blocks.

Fault scarps that have been removed by denudation may again be brought to light in another cycle of erosion. The Falls of Montmorency, near Quebec, are across a fault line in which ancient crystalline rocks have been brought up against much younger and softer beds; the fault scarp had been so entirely worn away that upthrow and downthrow side were on the same level, but the cataract cut a gorge which has been extended along the line of fault by the subaërial agents, and a new scarp, or, rather, the old one at a lower level, is being brought to light.

Another kind of topographical control which faults exert is less direct, but not less real, namely, in fixing the locality of river valleys. As has been shown previously, valleys may be formed by folding or by faulting (trench or rift valleys), and such tectonic valleys may or may not have streams flowing in them. The great majority of stream valleys were excavated by the streams which flow in them, with the coöperation of the atmosphere, in greater or less degree, but the location of the line along which the stream shall excavate is often fixed by a preëxisting fault. Faults are often lines of weakness, not clean-cut fissures, but bands of shattered rock, which are readily removed by running water. Such valleys are very common in the Sierra Nevada and the Great Basin and in the Coast Range of California. In the Adirondacks, the streams so generally follow the lines of faulting that, as seen on map, the regularity of the system is very remarkable and has given rise to the term *lattice drainage*. The Ausable Chasm, so frequently referred to, which is in the eastern part of the Adirondacks, has had its location determined partly by fault lines and partly by lines of jointing.

A stream following the course of a fault, in England, is shown in Fig. 103, and this is a very unusually favorable example, because the cliff in the foreground cuts across the plane of faulting and shows it in section.

E. Topographical Influence of Joints

All consolidated rocks, whatever their nature, are divided into blocks by planes, more or less distinctly shown, of parting, which

are called *joints*, and the joint blocks, which vary greatly in size and shape, are characteristic of the various kinds of rock. The same variety of rock, as granite, or diabase, or marble, may have very different kind of jointing in different localities, but, on the whole, the character of the jointing, especially of the sedimentary rocks, is constant. In determining the details of topography and drainage, joints play an exceedingly important rôle, because they are the planes of weakness through which water penetrates, and frost and other denuding agents attack the rocks. The undermining action of springs and rain causes hard beds to yield by the fall of unsupported blocks. Master joints which run through several strata and continue for long distances should probably be regarded as incipient faults without noticeable throw.

The minor drainage lines of a district are often fixed by the direction of the joints and their relation to one another. Wherever this matter has been examined with care and accuracy, as has been done in France, in Connecticut, and Wisconsin, it is found that the network of small streams is manifestly guided by the system of rock-jointing in that area. The course of the Zambesi River in southeastern Africa, below the wonderful Victoria Falls, is an unusual example of a large stream guided by the system of joints in the basaltic lava flows, through which the river has cut a narrow gorge, 400 feet in depth. (See Fig. 110.)

The great variety of land surface relief, caused, as we have seen, by the interplay of climate, the attitude and arrangement of the rocks, is only a passing phase in the history of the continents. The subaërial agents produce the peneplain, and the sea cuts the plain of marine denudation, both kinds of denuding forces working to destroy relief, until a renewed uplift shall initiate a new cycle of topographical development.

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"Earth Sculpture" is an epitome of Physiography, and to give authorities for the statements made in the foregoing chapter would require a long list of papers and books. The American point of view is well summed up in the works of Davis and of Salisbury and the German in that of Supan.

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Page numbers marked with an asterisk (*) indicate figures. Where several references are given under one heading, the most important are in heavy-face type. Names of the *genera* and *species* of animals and plants are in italics; names of persons, in capitals.